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DESTRUCTION AND STABILIZATION OF SLUDGE BY MULTIPLE-STAGE DIGESTION AND THERMAL TREATMENT

by

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16. ABSTRACT

This study compared conventional, anaerobic sludge digestion and three stage, anaerobic sludge digestion. The conventional digester and the first two stages of the multiple stage system were operated at 35°C; the third stage was maintained at 49°C.

The influent feed sludge was a mixture of primary and secondary sludges. Tests were run in three phases with solids retention times of 9, 15, and 20 days. Chemical oxygen demand (COD) loadings ranged from 2.4 to 8.8 kg COD/m^3-day; and volatile solids (VS) loadings ranged from 1.3 to 4.0 kg VS/m^3-day.

The results of this study indicated that multiple stage digestion outperformed conventional single stage digestion in terms of COD and VS destruction, and methane production. The first two stages of the multiple stage system, by themselves, achieved a greater degree of sludge stabilization and destruction, and methane production than the conventional system.

The effluent sludges from both processes were further treated by wet air oxidation (WAO). The WAO tests were performed at a pressure of 1.4×10^7 Pa (2,100 psi) and temperatures up to 300°C. The WAO process achieved 86% volatile solids reduction at 250°C. The major products of the WAO treatment were ammonia, acetic acid, organic nitrogen compounds, carbon dioxide, and water.

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FOREWORD

The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water systems. Under a mandate of national environmental laws, the agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. The Clean Water Act, the Safe Drinking Water Act, and the Toxic Substances Control Act are three of the major congressional laws that provide the framework for restoring and maintaining the integrity of our Nation's water, for preserving and enhancing the water we drink, and for protecting the environment from toxic substances. These laws direct the EPA to perform research to define our environmental problems, measure the impacts, and search for solutions.

The Water Engineering Research Laboratory is that component of EPA's Research and Development program concerned with preventing, treating , and managing municipal and industrial wasewater discharges; establishing practices to control and remove contaminants from drinking water and to prevent its deterioration during storage and distribution; and assessing the nature and controllability of releases of toxic substances to the air, water, and land from manufacturing processes and subsequent product uses. This publication is one of the products of that research and provides a vital communication link between the researcher and the user community.

The work presented here describes the use of a multiple stage anaerobic digestion system to destruct and stabilize mixed primary and secondary sludges from the Allegheny County Sanitary Authority. For process comparison, a conventional single stage digester was operated under the same loading conditions as the multiple stage system. However, the primary goal of this investigation was to determine whether

volatile solids reduction and gas production were improved by carrying out the hydrolysis, acidification, and methanation reactions in three separate fermenters . This study also investigated the dewatering properties and thermal destruction by a wet air oxidation process of the digester effluent sludges.

Francis T. Mayo, Director

Water Engineering Research Laboratory

ABSTRACT

A series of laboratory experiments was conducted at the Environmental Engineering Research Laboratory of the University of Pittsburgh to compare the performance of a conventional, single stage, anaerobic sludge digestion and three stage, anaerobic sludge digestion. The conventional digester and the first two stages of the multiple stage system were operated at 35°C; the third stage was maintained at 49°C.

The influent feed sludge was a mixture of primary and secondary sludges supplied by the Allegheny County Sanitary Authority. Tests were run in three phases with these operating parameters: SRTs of 9, 15, and 20 days; COD loadings of 0.31, 0.51, and 0.22 lb/cu ft-day ; VS loadings of 0.14, 0.24, and 0.10 lb/cu ft-day ; and acetic acid loadings of 0.0057, 0.0093, and 0.0019 lb/cu ft-day.

The results of this study indicated that multiple stage digestion outperformed conventional single stage digestion in terms of COD and VS destruction, and methane production. The first two stages of the multiple stage system, by themselves, achieved a greater degree of sludge stabilization and destruction, and methane production than the single stage system.

The effluent sludges from both processes were further treated by wet air oxidation (WAO). The WAO tests were performed at a pressure of 2,100 psi and temperatures between 105°C and 300°C. Total solids contents were 2.7% to 9% for digested sludge and digested, dewatered sludge.

The WAO process achieved 86% volatile solids reduction at 250°C. The WAO effluent solids settled well and yielded a low sludge volume index value. The major products of the WAO treatment were ammonia, acetic acid, organic nitrogen compounds, carbon dioxide, and water. The concentration of these products was dependent on the temperature and the total solids content of the WAO influent. Metal examination of the WAO effluent sludge samples indicated that no Cd, Cu, Mn, and Zn were found in the filtrate.

This report was submitted in fulfillment of Interagency Agreement No. DW-930244 by the University of Pittsburgh, under the sponsorship of the U. S. Environmental Protection Agency, the U. S. Army Construction Engineering Research Laboratory, and the Allegheny County Sanitary Authority. This experimental work covered the period from June 1, 1983 to December 31, 1984; the report was completed as of April 15, 1986.

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ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS

AA	--atomic absorption
CFST	--continuous-flow stirred tank
COD	--chemical oxygen demand
cu ft(ft^3)	--cubic feet
GC	--gas chromatograph
HRT	--**hydraulic residence time**
lb	--pound
mg/l	--milligram per liter
ml/g	--milliliter per gram
mmhos/cm	--millimhos per centimeter
MS	--multiple stage system
ORP	--oxidation-reduction potential
SCF	--standard cubic feet (at 25°C, 1 atm)
SRT	--solids retention time
SS	--single stage system
SVI	--sludge volume index
TS	--total solids
VS	--volatile solids
WAO	--wet air oxidation

SYMBOLS

C	--carbon
CH_4	--methane gas
CHO	--carbohydrate
CO_2	--carbon dioxide
COD_{CH_4}	--COD equivalent of produced methane gas
COD_{eff}	--effluent COD, weight/volume
COD_{in}	--influent COD, weight/volume
k	--maximum rate of substrate utilization per unit mass of microorganisms

K_c --endogenous decay coefficient, $time^{-1}$

K_s --half-velocity constant, substrate concentration at one half of the maximum growth rate, mass/volume

N --nitrogen

NH_3 --ammonia

NO_2 --nitrite

NO_3 --nitrate

P --phosphorus

Q --flow rate, volume/time

S_o --the initial substrate concentration, mass/volume

S_t --the substrate concentration at time t, mass/volume

U_{max} --maximum specific growth rate, $time^{-1}$

V --reactor volume, volume

X --concentration of microorganisms, mass/volume

X_o --concentration of microorganisms in reactor, mass/volume

Y --yield coefficient, defined as the ratio of the mass of cells formed to the mass of substrate consumed, mass/mass

θ --hydraulic detention time or solids retention time

METRIC CONVERSION

Length	
ft	-- 0.3048 m
in	-- 2.54 cm
Mass	
lb	-- 0.4536 kg
Volume	
ft^3	-- 28.317×10^{-2} m^3
in^3	-- 16.3871 cm^3
gal	-- 3.7854×10^{-3} m^3
Pressure	
psi	-- 6.8948×10^3 Pa (N/m^2)
Temperature	
^oF	-- 0.555(^oF - 32) ^oC
Organic Load	
lb COD/cu ft-day	-- 16.0 kg COD/cu m-day
lb VS/cu ft-day	-- 16.0 kg VS/cu m-day

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SECTION 1

INTRODUCTION

USE OF ANAEROBIC DIGESTION

Anaerobic digestion is one of the most widely-used unit processes today for sludge stabilization and volume reduction. It involves the biological conversion of organic solids to methane and carbon dioxide and some decomposition of inorganic matter in the absence of molecular oxygen. The sequential mechanism of this process is illustrated in Figure 1. The major applications are the stabilization of wastewater sludge,and the treatment of a number of industrial wastes.

Anaerobic digestion has several important advantages over aerobic biological treatment processes. These advantages are (a) low sludge production, (b) high applicability for treating both liquid and solid wastes, (c) the ability to break down complex organic compounds at high concentration, (d) a high kill-rate of pathogenic organisms, (e) the production of a useful gas (methane), and (f) comparatively better sludge compaction and dewatering characteristics (1,2).

In spite of the present significance and future potential, anaerobic digestion processes have not enjoyed a favorable reputation for several reasons: (a) the high degree of empiricism that is generally seen in the design and operation; (b) the lack of complete fundamental knowledge about the physical, chemical, and biochemical interactions; (c) mixing and heating problems; and (d) the slow destruction of fats and greases(3,4). Thus to make full use of this waste treatment and energy production technology, it is necessary to investigate improvements in digester and process design.

Biological degradation of particulate organic matter to methane follows six distinct processes:

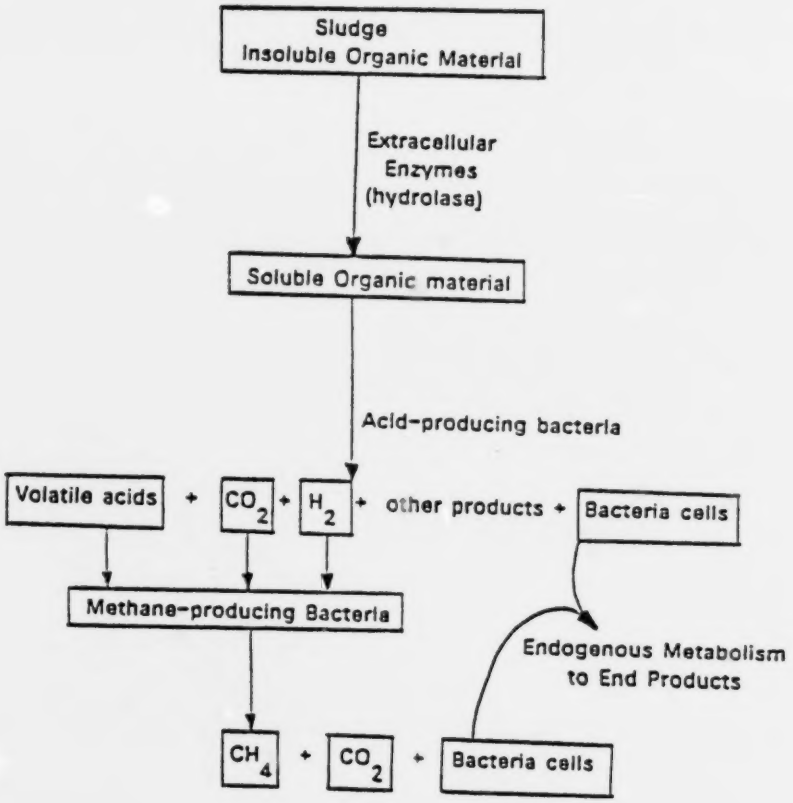


Figure 1: Sequential Mechanism of Anaerobic Digestion

1. Hydrolysis of biopolymers (i.e., volatile solids containing proteins, carbohydrates, and lipids).

2. Fermentation of amino acids and sugars.

3. Anaerobic oxidation of long chain fatty acids and alcohols.

4. Anaerobic oxidation of intermediate products (propionate and butyrate) to acetate and hydrogen.

5. Conversion of acetate to methane.

6. Conversion of hydrogen to methane.

In the past, studies have concentrated on steps 4, 5, and 6. Investigation of reactions 1-3 has only partially been made(6,7).

THE CURRENT STATUS OF RESEARCH ON MULTIPLE STAGE DIGESTION

Before anaerobes can effectively use biopolymeric substances, these organics first must be broken into soluble polymers and monomers. The reactions are generally described as the liquefaction or hydrolysis of complex biopolymers and they are brought about by an extracellular enzyme at a relatively slow rate, particularly in the presence of lipids. Termofil (8) reported that the hydrolysis step might be overall rate-limiting in the anaerobic digestion process, when the wastewaters or particulate organic materials contain a considerable amount of lipids. Eastman and Ferguson (9) also found that the rate of hydrolysis was the limiting factor in the acid phase of digestion.

The acid production rate is highly dependent upon the content of soluble, degradable organics in the liquid or particulate organic waste. With more degradable organics there will be more acid accumulation, which might limit methane generation. Acid formers come in two types: acid-producing bacteria and acetogenic bacteria. The acid-producing organisms respond quickly to change in organic loads and generate volatile acids(especially acetic, butyric, and propionic), which reduce the pH of the solution. Acetogenic bacteria are capable of converting either propionic acid or butyric acid into acetic acid. These bacteria grow slowly even under the optimum conditions of a low hydrogen concentration (10). Acid-producing and acetogenic bacteria have a minimum cell doubling time of 2 to 3 hours and 1.5 to 4.0 days, respectively, at 35°C (3,10). According to Ghosh and Klass (3),

the maximum specific growth rate, yield coefficient, and half velocity constant of acid formers are 3.8 day^{-1}, 0.4, and 37 kg COD/m^3, respectively. These data were obtained at 37°C with activated sludge in a two-phase digestion system.

Methanogens are acetoclastic methane bacteria and H_2-utilizing methane bacteria which produce methane from the utilization of acetic acid, hydrogen and carbon dioxide. Normally, the H_2-utilizing methane bacteria grow rapidly compared to the acetoclastic methane bacteria; but generally, 70% of the total methane is produced by the acetotroph.

Some average values of the maximum specific growth rate, yield coefficient, and half velocity constant of anaerobic cultures in single and two stage digester systems are summarized as follows (11):

Table 1: Single-phase and Two-phase Digestion Data

Culture (at 30°-38°C)	Maximum Specific Growth Rate day^{-1}	Yield Coefficient kg VSS/kg COD	Half Velocity Constant kg COD/m^3
A. Two-phase			
Acetic acid Producing Bacteria	1.50	0.15	0.2
Methane Producing Bacteria	0.30	0.03	0.05
B. Single-phase Combined Culture	0.30	0.18	-

The table shows that a profound increase in the maximum specific growth rate of acetic acid producing bacteria occurred when the acid-producing bacteria were cultivated separately from methane formers. In other words, the anaerobic digestion process could become more effective in the hydrolysis of sludge solids and the production of volatile acids as a result of stage separation. In addition to stage separation, the anaerobic digestion reactions can be accelerated by maintaining high concentrations of acid formers and methane formers in the digesters.

The preceeding discussion noted that there is a substantial difference in the metabolic characteristics of the acid and the methane formers. Therefore, some

researchers have envisioned controlled anaerobic stabilization and gasification of sludge solids by separating the two groups and culturing them in isolated environments (12,13,14). Optimum environments could then be provided for each group of organisms; the substrate loading rates to each group could be controlled, which would enhance process efficiency and reliability.

A recent advance in sludge digestion has been to use mesophilic digestion followed by thermophilic digestion to expose the solids undergoing digestion to a series of enzyme systems in order to increase significantly the degree of volatile solids destruction (18). This process, which has been called multiple digestion by Torpey and co-investigators, has the additional advantages of increasing the pathogen kill, reducing the coagulant requirements markedly, and decreasing the sludge volume for disposal.

The use of acidic digestion prior to mesophilic digestion, which has been discussed earlier, is expected to decrease the overall tankage requirement, and more importantly, to increase the degree of destruction of volatile matter. This separation of the acid formation phase from the acid-to-gas conversion phase should result in capital and operating benefits. In addition, it is anticipated that this phase separation will considerably reduce or eliminate foaming in mesophilic digestion. It is reasonable to expect that preceding multiple digestion with acidic digestion will add to the already high volatile solids destruction achieved with multiple digestion. The union of the above into a common process requires three stages: acid digestion, mesophilic digestion, and thermophilic digestion. Thus the combined effects of the three consecutive biochemical processes should be evaluated to determine their capacity for destruction of the volatile matter in wastewater sludge. The investigation of this combined sludge digestion technique focuses on the specific objective of increasing the degree of biochemical destruction of volatile matter, and secondarily, doing this at a resonably high rate.

Postulated advantages of the multiple stage digestion system can be generally characterized by:

1. An improved digester stability which results from staging

2. An increased destruction of sludge solids by providing favorable conditions for reaction in each treatment stage

3. An acceleration of digestion reactions by retaining a high concentration of acid and methane formers in the digesters

4. A separation of the reaction of hydrolysis from the acidification which will increase the reactions of acidification and methanation

5. An acceleration of the production of methane

6. A more pathogen-free effluent

7. A higher organic loading and lower detention times (15,16)

However, this digestion process also has potential disadvantages:

1. A need for skilled operation

2. A need for more instrumentation, monitoring, and control

THE CURRENT STATUS OF RESEARCH ON WET AIR OXIDATION

It is necessary to treat the metals and toxic organics leaving the last stage of the digestion system in order to make the sludge disposable in an environmentally-satisfactory manner. Wet air oxidation (WAO) which uses elevated temperatures and pressures to oxidize materials in the aqueous state (20), can be used to cope with these contaminants. This process has been demonstrated to be capable of oxidizing heavy metals, thus making them insoluble, destroying toxic organics, and effecting a reduction in sludge volume of some 98% (19) In the process, solids are solubilized, and through hydrolysis reactions, these complex hydrocarbons are broken down. More importantly, these thermochemical reactions are flameless. Hence, the main product of the wet oxidation process is carbon dioxide along with some organic acids.

According to Randall and Knopp (21), the WAO process is well suited for the treatment of dilute aqueous wastes that would be too expensive to incinerate and might be too toxic for direct biological treatment. At temperatures of 275°C and 320°C, a pressure of 3,000 psi, and with and without copper catalysis, a high degree of destruction and detoxification of organic compounds can be achieved. In addition, Mueller and Su (22) indicate that a benthal oxygen demand is reduced approximately 50% by low-pressure wet

oxidation and 90% by high-pressure wet oxidation. The WAO process is also flexible enough to accomodate wide variations in waste stream composition or pulses of toxic materials, each of which is destructive or harmful to biological systems. It can be used where the specific concentration is high to decrease the plant wastewater load or where the plant unit is too limited for biological treatment.

A study of thermochemical stabilization of digested sludge at New York Rockaway Pollution Control Plant revealed that more than 95% of protein, carbohydrate, and lipid in digested sludge could be reduced by WAO and that this high performance was obtained with operating conditions of 200 to 260°C & 800 psi. Also, the same investigation found that the complete removal of priority pollutants such as acenapthene, acrolein, 2,4 dimethylphenol, and pentachlorophenol could be attained at a temperature as low as 250°C (23).

A question arises as to the fate of metals undergoing the WAO process. The thermal treatment of anaerobically digested sludge has been reported to increase the solubility of Cu, Zn, and Ni, while not affecting the partitioning of Cd and Pb at operating conditions of 240 to 260 psi and 180 to 200°C (24,25). Other investigations have reported that for digested sludge 90 to 100% of most metals could be oxidized and precipitated at temperatures of 190°C and above (26). However, others report that most metal ions are unaffected by WAO and that metals in sewage sludge might be precipitated as sulfate, phosphates, oxides, hydroxides, or remain in solution (27).

Decreases in specific resistance , a measure of dewatering efficiency, have been reported after WAO treatment of waste sludge at 150°C (one to two orders of magnitude); a further order of magnitude decrease occurred at 170°C, which was followed by an apparent leveling off thereafter. The wet air oxidation of sludge also improved gravity thickening of sludge, with solids in excess of 10% readily achievable (28).

A report has indicated that WAO tests, run on wastewater sludges at 350°F for 3 minutes and at 240°F for 10 minutes, resulted in complete destruction of coliform, mold and yeasts. However, a test run at 240°F for 10 minutes indicated survival of fecal streptococci. Tests run at 120°F for 3 minutes and 30 minutes showed survival of microorganisms. The 3 minute test actually enhanced microbial growth conditions. In addition, for complete disinfection the critical conditions were found to be 10 minutes at 250°F, 0.6 minute at 275°F, and 0.061 minute at 300°F, and 0.015 minutes at 300°F (29).

Detoxification of specific organic substances, precipitation of heavy metals, and improvement of the thickening characteristics of digestion sludge are the major advantages of this process. However, one objection to the WAO process has been its relatively high capital and operating costs with respect to other treatment technologies, in particular, biological treatment. In such cases, these costs are generally based on the replacement of biological treatment (anaerobic digestion) with WAO. Such costs would be lower if WAO technology were applied to sludge after anaerobic digestion because the volume of sludge to be treated has been reduced. This material has exhausted its capacity for biological degradation, and as such, it requires physiochemical treatment for further breakdown. As tertiary treatment, WAO can offset many of the sludge handling problems associated with anaerobic digestion (16).

PURPOSE AND OBJECTIVE OF THIS PROJECT

To prove experimentally the practicability of this sludge treatment technology, the research was planned to study the effect of the operational mode on the performance of an integrated sludge system (three-stage digestion followed by wet air oxidation). This integrated sludge digestion process consisted of three seperate bioreactors connected in series. The first digester was controlled at mesophilic temperature and it was used for hydrolysis and acid digestion of sludge solids. Although the second digester was controlled at the same temperature as the first digester, it was mainly employed for a biological conversion of volatile organic acids to methane gas (i.e. acidification-methanation). The last stage of this multiple digester system was designed to achieve the same purpose as the preceeding second stage. However, this thermophilic digester has the following unique characteristics:(a) to further breakdown the volatile organic solids and to produce additional methane gas, (b) to generate an odor-and-pathogen-free effluent, (c) to improve the digested sludge dewaterability. Anaerobic digestion of the sludge helps to reduce the volume of solids but it does not lower levels of compounds such as some aromatics and metals. Anaerobic digestion, by reducing solids, tends to concentrate these materials. In addition, anaerobic sludge is often more difficult to settle or filter than raw sewage sludge. WAO was then used to further reduce sludge volume and pathogens, and eliminate or safely stabilize toxic compounds and metals.

The main objectives of this research were (a) to investigate whether volatile solids

destruction, gas production, settling and dewatering properties of sludge, and effluent quality in terms of coliform bacteria concentration were improved by multiple stage digestion as compared with single stage digestion, (b) to determine the effects of organic and volatile solids loadings and solids retention time on the digestion efficiency, (c) to evaluate kinetic data for both systems as well as for each digester of of the multiple stage digestion system, (d) to study the biogas generation, (e) to examine the filtering and settling characteristics of the digested sludges, and (f) to determine the effects of temperature and sludge concentration on performance of WAO and the WAO effluent sludge settleability.

SECTION 2

CONCLUSIONS

MULTIPLE STAGE DIGESTION

The multiple stage system outperformed the single stage system in terms of COD reduction, VS reduction, and methane production, as follows:

	Multiple Stage	Single Stage
COD (% removal)	44 - 59	32 - 44
VS (% removal)	59 - 67	44 - 50
Methane (L/day)	112 - 247	21 - 81

Together, the first two stages of the multiple stage system were more efficient than the single stage system, even though the total retention time was 35 percent shorter.

The second stage of the multiple stage system, by itself, had greater total methane yield and methane production rate than the single stage system, although the retention time in the second stage reactor was only 55% of the single stage retention time.

The third stage of the multiple stage system gave the following benefits which have to be weighed against the economic costs of adding a third stage.

- an additional 2.0 log reduction in coliforms
- a 15-19% increase in methane
- a 23-30% further reduction of COD
- a 27-36% further reduction of VS

Separation of the digestion process into stages did not create a need for chemical addition to control alkalinity and pH.

Hydrolytic and liquefying reactions occurred in all three reactors of the multiple stage system, as evidenced by reductions in lipids, proteins, and carbohydrates in all three reactors. Overall reduction of these compounds was greater in the multiple stage system than in the single stage system.

At longer retention times in the first stage reactor excessive foaming became a problem. Therefore a first stage residence time of about one day should be used.

Dewatering and settling characteristics of the multiple stage digested sludge were only slightly better than for the single stage digested sludge.

Metals (Cd, Cu, Mn, Ni, Pb, and Zn) partitioned to the sludge rather than the supernantant in the effluents from both systems.

WET AIR OXIDATION

The principal products from the wet air oxidation (WAO) of the digested sludge were volatile acids, nitrogen compounds, carbon dioxide, and water.

The effluent from the WAO was usually slightly basic.

The best VS destruction occurred at an oxidation temperature of 250°C. VS destruction of 86% was constant and independent of influent VS concentration.

Organic nitrogen was broken into ammonia nitrogen, nitrate, and nitrite, although some reformation of organic nitrogen compounds from these products and organic acids appeared to occur at higher temperatures.

Sludge filter cake (>4% VS) was not destroyed as effectively as lower solids sludges, probably because of an oxygen limiting condition.

The sludge destruction occurred primarily at temperatures above 180°C and increased with temperature.

The settling characteristics of WAO effluent solids improved with increasing temperature, and SVI values less than 18 ml/g were possible.

INTEGRATED SLUDGE TREATMENT PROCESS (MULTIPLE STAGE DIGESTION FOLLOWED BY WET AIR OXIDATION)

If the multiple stage digestion system is operated in conjunction with WAO, the total destruction of volatile solids can reach as high as 95.5 percent. However, using only a two stage digestion system should be considered if WAO is utilized. The savings in digester volume, heating, and mixing may offset the additional costs needed for wet air oxidation without sacrificing the efficiency of volatile solids destruction.

The solids in the effluent of the integrated treatment system possessed excellent settling characteristics. The final process effluent had a pH of approximately 7.5 and it contained high levels of nutrients, such as ammonia, phosphorus, and organic nitrogen. However, it was found that the WAO effluent sludge was highly contaminated with metals. Thus metal stabilization and detoxicification might be required.

SECTION 3

RECOMMENDATIONS

Research is needed to optimize the size or SRT of each inividual digester in the multiple stage system to minimize the total volume and maximize the methane production and the reduction of volatile solids and COD.

A study is needed to determine the feasibility of recycling a portion of the sludge leaving the third digester to an activated sludge plant, which might further increase the degree of volatile solids destruction.

Further investigation is needed to determine the effects of upstream **recycling or** separate treatment of WAO effluent. Toxicity, mutagenicity, and anaerobic and aerobic inhibition tests should be performed.

Confirmation is needed of previous investigations by other researchers which showed that WAO destroys many priority pollutants that may be present in sewage sludges.

WAO may produce harmful agents, or toxic levels of various compounds (e.g., ammonia). Therefore, it is strongly recommended that further studies take place to investigate possible mutagenic or toxic properties of WAO supernatants and sludges.

Studies are needed to determine a relationship between temperature, solids concentration, and oxygen limiting conditions for WAO. These studies could be conducted at various pressures for a given temperature, and could aid in optimizing the operation of the system.

A cost/benefit analysis is needed to determine whether the benefits of higher digestion efficiency and smaller digester volume requirement for the multiple stage system offset the additional capital, operating, and maintenance costs of the extra equipment.

A cost/benefit analysis is also needed to determine the **feasibility** of applying multiple stage digestion followed by wet air oxidation for destroying virtually all of the sludge solids and producing a pathogen free effluent.

SECTION 4

MATERIALS AND METHODS

The general design consisted of a conventional, single stage digester, and a multiple stage anaerobic digestion system followed by wet air oxidation (WAO). Biological conversion of sludge solids to methane gas was carried out by anaerobic digestion and the digester effluent solids were further destroyed by the thermal treatment.

ANAEROBIC DIGESTION EQUIPMENT AND OPERATING PROCEDURES

Anaerobic Digestion Units

The digesters for the multiple stage system were constructed of Plexiglass with effective volumes of 6, 30, and 18 gallons. A flow diagram of this digestion system is shown in Figure 2. The effective volume of the control system digester was 27 gallons, or one half of the total operating volume of the multiple stage system. Detailed dimensions of each anaerobic digester are in Appendix A.

The reactor contents were well mixed by a mechanical agitator equipped with a variable speed control. Each digester was heated by magnetic heat tape, which was wrapped around the reactor. The first two digesters were controlled at a mesophilic temperature (35°C) while the last digester was maintained at a thermophilic level (50°C).

Volumetric Gas Measuring System

The gas space of each digester was directly connected to the gas collection apparatus shown in Figure 3. Before the gas entered the collection system, it passed through a 250 ml gas sampling tube which could be removed from the gas line to permit CH_4 and CO_2 analyses.

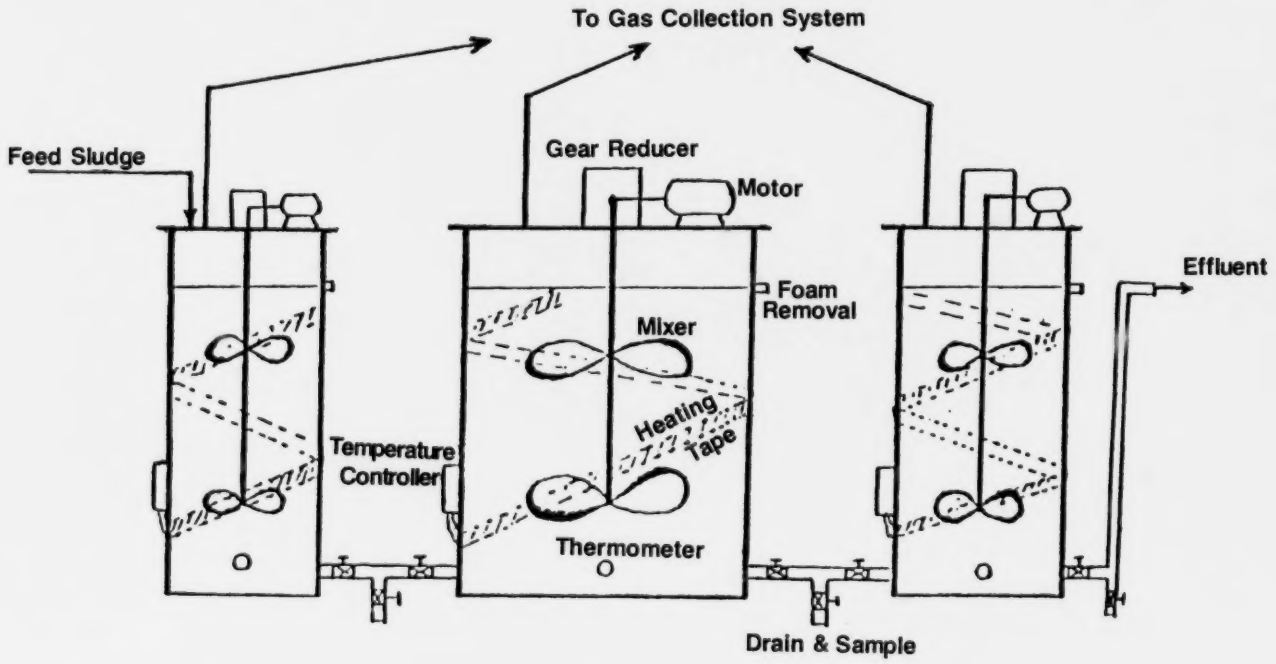


Figure 2: Multiple-stage Digestion System

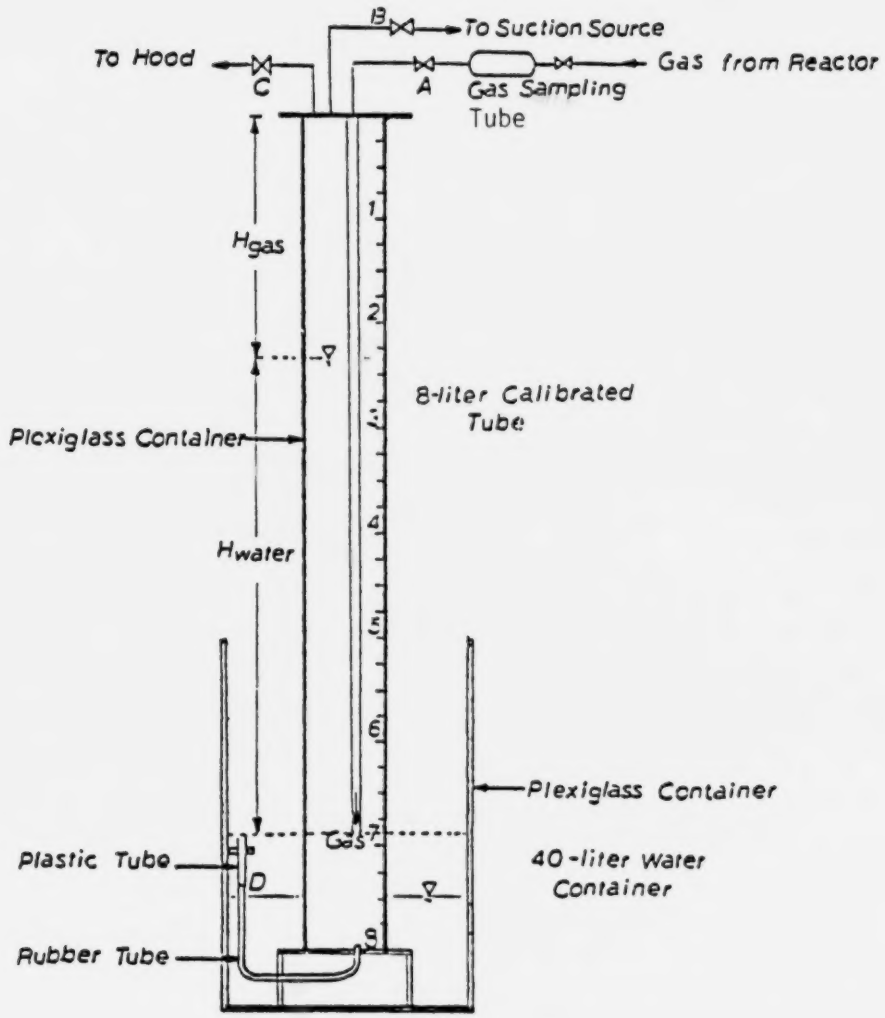


Figure 3: Gas Collection Apparatus

Normal procedures for operating the gas measuring system were as follows:

1. Fill the water tank to the level marked by dotted line.
2. Close valves A & C and disconnect D.
3. Apply vacuum through valve B until the water level rises to the top of the cylindrical gas collection chamber.
4. Shut off valve B and connect D
5. Open valve A, which allows the gas to displace water in the gas collection chamber as soon as the gas pressure exceeds 1 atm.
6. Wait until the water level inside the gas collection chamber drops to the dotted line (the original water tank level).
7. Read the total gas volume produced within the time period.
8. Remove the gas sampling tube for Orsat analysis of gas compositions.
9. Open valves A & C to by-pass the gas.

Since the same water was used repeatedly for gas measurement in this system, it was saturated with gas at all times. Therefore, the amount of gas absorbed by or dissolved into the water was minimized. This resulted in a precise measurement of gas production for each digester. The measurement of gas generation for both the test and control systems was taken three times each week when the analyses of other parameters were performed. The gas volume was determined by continuously collecting it for a period of 24 hours only on each sampling day. Analyses of CH_4 and CO_2 content in gas were also done on the same day when it was collected.

Seed Organisms

The mesophilic digesters were seeded with digested sludge from the Sandy Creek Wastewater Treatment Plant located at Penn Hills, Pennsylvania. The thermophilic digester was inoculated with seed from a thermophilic digester at the Rockaway Wastewater Treatment Plant in Rockaway, New York.

Source of Sludge

Approximately 50 gallons of sludge was obtained on Monday and Thursday each

week from the Allegheny County Sanitary Authority (Alcosan) wastewater treatment plant located in Pittsburgh, Pennsylvania. The sludge was a mixture of primary and secondary sludges with a solids concentration of 3-5%. After the sludge was removed from the clarifiers, it was transferred immediately to the University of Pittsburgh Environmental Engineering Laboratory. Raw sludge was manually screened through two layers of 1/4"-square opening Neo-mesh wire for grit removal and then stored at 4°C.

The sludge was fed to the digestion systems by an UltraMaster pump (Master Servodyne Pump Drive). The pump was connected with three standard Masterflex heads (two for feeding the multiple stage system and one for feeding the single stage system). The sludge was fed directly into the first reactor of the multiple stage system and the single stage system and then allowed to flow through the subsequent reactors by gravity. Using a timer, the sludge was pumped for 15 minutes each hour at flow rates of 0.45, 0.60, and 1.125 gal/hr, producing an SRT equal to 20, 15, and 9 days, respectively, in the multiple stage system. The rate of sludge feed to the single stage system was controlled to be equal to one-half of that used for the multiple stage system in order to obtain virtually identical SRTs for the control and test digestion units.

Digestion Startup and Sample Collection

The startup and development of the anaerobic digestion systems began on October 2, 1983. Immediately after the seed sludges were added to the mesophilic and thermophilic digesters, fresh sludge was fed to produce an SRT approximately equal to 15 days in both systems.

During the first 10 days, 2,000 mg/l of sodium bicarbonate were mixed with the feed sludge to assure that the alkalinity was sufficient for maintaining a proper growth condition in each digestion system. The alkalinity addition was then eliminated because of plans to test whether the proposed multiple stage system could be operated without alkalinity control on the feed sludge.

No sludge samples were withdrawn for analysis until November 2, 1983. Sludge and gas samples were collected three times per week from the feed sludge and each digester. Sample sites were selected to ascertain the properties of the sludge influent and effluent for each reactor. A 500 ml sample was taken via sampling ports and glass

receptacles from each sampling location. Although these sample volumes were large, they had a negligible effect on SRT (less than 3% change in volume).

To avoid contamination, all glassware was pre-washed with the appropriate dilute acid or solvent washes and dried prior to use. Division of each sample into aliquots for the individual tests was carried out immediately after sample acquisition with clean pipettes and/or graduates to avoid contamination.

Since all tests were conducted on a fresh sample, no preservation was necessary except for atomic absorption analysis. Here, the sample was either dried, pulverized and stored in glass or acidified and stored in polyethylene containers at 4°C.

WET AIR OXIDATION EQUIPMENT AND OPERATING PROCEDURES

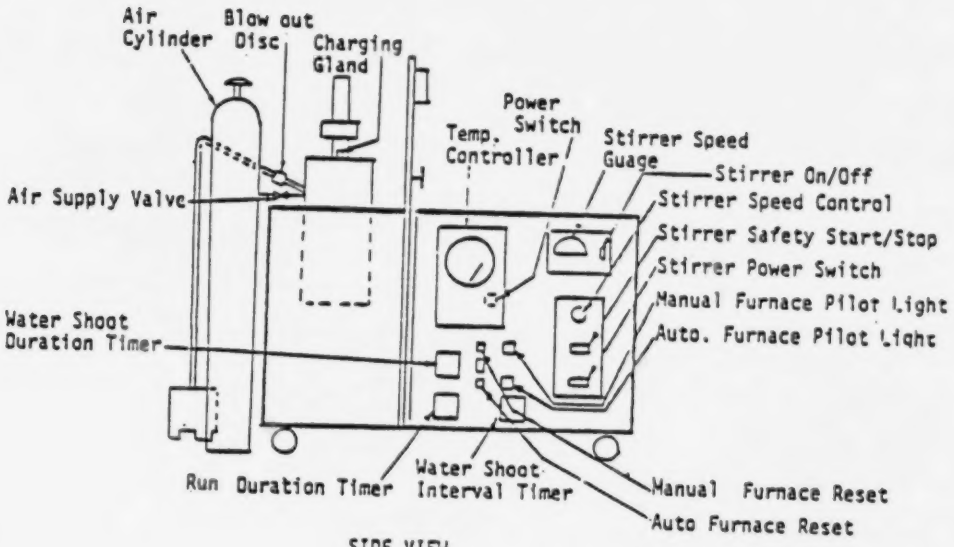
Equipment Description

The WAO apparatus was designed and loaned by Zimpro Inc. of Rothschild, Wisconsin. The autoclave reactor was a one gallon, insulated, aluminum jacketed, titanium vessel rated at 2,250 psi. The unit is shown schematically in Figure 4.

Two furnaces regulated the temperature automatically by means of a Honeywell Electronik III controller-chart recorder. A third furnace would shut down 10°C before the unit reached the test temperature (set point). The power level for each furnace was controlled by a Powerstat variable autotransformer. The temperature was measured by an iron-constantan thermocouple; the pressure was measured by a sealed, all stainless steel gauge. Additional temperature control was available through a timed, electrically-activated, Ascolectric gate valve, which provided intermittent bursts of cooling water through a 1/4" titanium cooling coil.

A belt-magnetic drive stirrer was driven by a 1/4 HP variable speed DC motor; the mixing speed was set at approximately 500 rpm. The stirrer consisted of a hollow shaft titanium rod tipped with a 1/2" X 2" titanium paddle. Aspirator inlet and outlet holes were located at the top and bottom, respectively, of the stirred shaft to supply extra agitation by air bubbles.

FRONT VIEW



SIDE VIEW

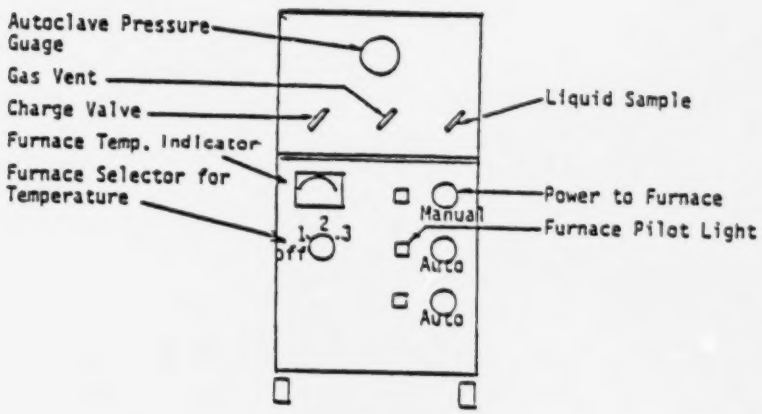


Figure 4: Wet Air Oxidation Apparatus

The autoclave sludge inlet/outlet was a 3/8" port sealed with a titanium gland. Valves, fittings, and rupture disk were supplied by Autoclave Engineers Inc. of Erie, Pennsylvania.

At the end of a test, a timer shut down the two operating furnaces and initiated the flow of cooling water through a second gate valve. A third timer controlled the duration of the water burst, but it was inoperative for the test period and could only give one second bursts of water. After a test had been cooled to room temperature, air was vented from the vessel via a Single DTM-115 air volume meter and a polypropylene gas sampling tube.

Operating Procedure and Sample Collection

Appoximately 50 liters of digested sludge were collected from both effluents of single stage system and the final stage of the multiple stage system. These sludges were centrifuged to 11% solids and 0.4% solids in the supernate. The samples were collected and stored at 4°C in a sealed, glass jar and a sealed Nalgene carboy, respectively. Prior to charging the WAO reactor, the sludge was vigorously hand-mixed with a plastic rod for 2 to 3 minutes. A set of sludge samples was prepared by dilution with supernatant or filtrate to concentrations of 2.7%, 5%, 7%, and 9%.

Sludge was inserted through the charging port by a sludge syringe or a plastic funnel. The autoclave was sealed, presssurized, and heated to the desired temperature. At 150°C and above, the operating pressures were based upon Zimpro's recommendation of suppling 120% of oxygen required for complete destruction based on COD.[1] Since the autoclave was operated at its upper limit of recommended holding pressure, the unit had to be monitored constantly by the operator. The autoclave maintained its temperature automatically at the pre-set temperature; nevertheless, the temperature and pressure were monitored constantly. The charging time required for getting to the pre-set temperature point in autoclave was one hour.

After the sample oxidation was completed, the autoclave was cooled to room temperature by passing cooling water through the coil. A 1.5 to 3.0 hour cooling period

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[1] See Appendix B

was required after each test. The duration was determined by the test temperature and, to a larger extent, by the temperature of the cooling water. Usually, the autoclave was cooled to 25°C; although, when cooling was particularly slow, the contents were removed at 30 to 35°C.

Upon completion of cooling, the air was sampled for Orsat gas analysis, measured to record the volume, and vented. After removing the charging gland, the sample was sucked from the port to a one liter aspirator bottle, while mixing with a Teflon-covered stir bar and stirrer. The autoclave was rinsed until the water was clear, then the autoclave was disconnected from the power source.

Samples were immediately analyzed for all of the parameters listed in Table 2 except for metals; these samples were preserved for later analysis. It is important to mention that instability characterized the reading of pH, ORP, and conductivity. It was found that the slow rise of these parameters could be nearly arrested by sealing the beaker with paraffin. As such, these values reported are of limited meaning.

ANALYTICAL TECHNIQUES

The major performance parameters and the analytical methods employed for the study are listed in Table 2.

Total and total volatile solids, COD, pH, conductivity, organic nitrogen, lipids, and coliform bacteria, were determined in accordance with "Standard Methods" (30). Anthrone and Buiret tests developed by Gaudy (31) were used to measure sludge protein and carbohydrate. Total soluble phosphorus and alkalinity were determined by following the techniques proposed by Gales, et al. (32) and Jenkins, et al. (33). Oxidation-Reduction Potential (ORP), ammonia-N, nitrate-N and nitrite-N were measured by Orion Model 601A digital ion analyzer equipped with redox, ammonia, nitrate and nitrite electrodes. Organic acids (acetic acid, propionic acid, and butyric acid) were determined by the use of gas chromatograph in accordance with analytical method as proposed by Ottenstein and Bartley (34). Methane gas, carbon dioxide, and O_2 were analyzed by the Orsat gas analyzer.

The solids settleability test performed on the WAO effluent samples, as well as the

Table 2: Experimental Parameters

Parameters	Sampling Point						Reference
	Raw Sludge	Sludge Digestion			Control System	Wet Air Oxidation	
		Multiple-stage System					
		1	2	3			
Total Solids	X	X	X	X	X	X	208A (30)
Total Volatile Solids	X	X	X	X	X	X	208E (30)
Total Soluble Phosphorus	X	X	X	X	X	X	(32)
Lipids	X	X	X	X	X		502C (30)
Carbohydrates	X	X	X	X	X		(31)
Protein	X	X	X	X	X		(31)
Ammonia N	X	X	X	X	X	X	Orion Model 601A
Nitrate/Nitrite	X	X	X	X	X	X	Orion Model 601A
Organic Nitrogen	X	X	X	X	X	X	412 (30)
Conductivity	X	X	X	X	X		205 (30)
ORP	X	X	X	X	X		
Alkalinity	X	X	X	X	X		(33)
COD	X	X	X	X	X	X	508 (30)
Organic Acids	X	X	X	X	X	X	(34)
Methane Gas		X	X	X	X		(30)
Total Gas Volume		X	X	X	X		
CO_2		X	X	X	X	X	Orsat
O_2						X	Orsat
Metals (Cd, Cu, Mn, Ni, Pb, Zn)	X			X	X		301A (30) & (35)
Settleability					X	X	213E (30)
Coliform Bacteria	X	X	X	X	X		909A (30)
Filterability				X	X		(36)

chemically-treated digester effluent samples was done in accordance with "Standard Methods". Metals were tested by flame atomic absorption spectroscopy. The procedures for sample preparation for dried sludge and filtrate were from "Test Methods for Evaluating Solid Waste/Physical Chemical Methods" (35) and "Standard Methods" (30), respectively.

SLUDGE DEWATERING EQUIPMENT AND PROCEDURE

The filtration apparatus was an 11-cm Buchner funnel, fitted into a polymethyl methacrylate vacuum cylinder with a rubber stopper. Set inside the vacuum cylinder was a 250 ml graduated cylinder, which was used to measure the volume of the filtrate. The funnel was prepared for the filtration test by first placing a piece of muslin cloth and then a filter paper (Schleicher & Schuell No. 589) over the filter area. Prior to the addition of sludge to the Buchner funnel, the surface of the filter paper was coated by the addition of 100ml of 10-g/l diatomaceous earth suspension. Sludge filtration was performed under a vacuum of 15 in of mercury supplied by a vacuum pump. For timing control, the vacuum pump was connected to a timer that automatically regulated the on-off position of the pump. This monitoring system could measure the filtration time easily and precisely.

The sludge filtration tests were conducted under two conditions; with and without the addition of chemical conditioner. The chemical conditioners were organic polymers, Magnifloc 581C and Magnifloc 1563C, manufactured by American Cyanamid Company. The applied concentration of chemical conditioner varied from 0 mg/l to 6,000 mg/l. If no sludge conditioner was added, a 200-ml portion of the sludge was filtered. When the chemical was applied, the total volume of chemical plus sludge was 200 ml. The sludge sample was mixed with the chemical for 5 minutes at 15 rev/min prior to the vacuum filtration test. No pH adjustment was given to the sludge after chemical treatment. In most cases, the sludge filtration test was completed in 8 minutes; the volume of the filtrate was recorded each 30 seconds.

The filterability of digested sludge was determined by the value of specific resistance. The general methodology for the measurement of specific resistance is discussed by Wu, Smith, and Novak (36).

QUALITY ASSURANCE PROGRAM

Quality Control

For each group of samples processed, blanks (distilled, deionized water and reagents) were carried throughout the entire preparation and analytical processes. These blanks were useful in determining if samples were being contaminated.

Duplicate samples were processed on a routine basis and they were used to determine precision. The sample load dictated the frequency; but 10% of the samples were generally analyzed in duplicate..

Spiked samples or standard reference materials were employed to determine accuracy. A spiked sample was included with each group of samples processed and whenever a new sample matrix was analyzed.

The concentration of all calibration standards was verified against a quality control check sample obtained from an outside source.

Treatability and Accuracy

Traceability of each instrument used was not needed, since few pieces of instrumental hardware were used and these are never removed from the control of the testing laboratory. The instruments used were: Bauch and Lomb Spectronic 20, Orion Model 601 Analyzer, Orsat gas analyzer, Orion Oxidation-Reduction Probe, and various Orion Ion Electrodes.

Traceability of data was accomplished by acquiring raw data, converting the data to the correct units, and recording the data in notebooks for eventual storage in computer data banks. Evaluation of the individual data for the whole project was accomplished by a computerized analysis of variance (ANOVA) and a multiple regression analysis for kinetic modeling. Traceability of standards and of samples was not applicable, since each sample was immediately analyzed and most analyses utilized a new standard curve for data analysis each time. The only exception to this was samples for atomic absorption analysis to detect the concentration of metals. Here, the samples were dried, stored weekly, and analyzed once a month. Such samples were labeled as to date, sample site, dry weight,

dilution volume necessary, and technician responsible. Spiked samples were utilized for the gas chromatograph (GC) and atomic absorption (AA) measurements of metals and organic acids.

Performance audits were run every six months. They were conducted on a rotational basis for the four research assistants, who handled the carbohydrate, protein, ammonia nitrogen, pH, alkalinity, COD, ORP, total volatile solids, total solids, gas volume, gas components, lipids, soluble phosphorus, settleability and filterability, temperature, and feed rate. That is, once every six months, a research assistant ran the analysis for one of his/her co-workers and compared the two values obtained. For the tests utilizing the gas chromatograph and atomic absorption, a non-project related, in-house GC and AA technician carried out the performance audit. The calculated accuracy and precision of each test parameter is given in Table 3.

Table 3: Precision and Accuracy

Test	%Accuracy (% Error)	Precision (%Relative Standard Deviation)	Reporting Units
Carbohydrate	5-15%		mg/l
Protein	30-50%		mg/l
NH_3-N	5-10%	±5%	mg/l
Total N	10-20%	±50%	mg/l
AA (Metals)	20%	±20-40%	mg/kg
Total Solids	5%	±5%	mg/l
Total Vol.Solids	6%	±6%	mg/l
Gas Volume	5%	±5%	liter/day
Gas Components		± 1%	% of gas
COD		±0.13%	mg/l
Alkalinity	5%	±5%	mg/l
ORP		± 1	mv
Conductivity		± 1%	mmhos/cm
Temperature		± 1%	^{o}C
pH	1%	±0.01	
Lipids	4-8%	4.6%	mg/l
Total Sol. P			mg/l
Filterability	5%	± 1%	m/kg
SVI	1%	±0.1%	ml/g
GC(Organic Acids)	5%	±5%	mg/l
Coliforms	5%	±5%	#/ml

SECTION 5

RESULTS AND DISCUSSION

OPERATIONAL CONDITIONS

Two laboratory scale systems, a multiple stage test system and a conventional single stage control system, were operated under the following conditions: three SRTs(9, 15 and 20 days); and two first stage SRTs when the overall SRT was 20 days; temperature control at mesophilic temperature(35°C) in the first and second stages of the test system and the control system, and thermophilic temperature(49°C) in the third stage of the test system; and loading varying from 0.15 to 0.55 lb COD/cu ft-day and from 0.08 to 0.25 lb VS/cu ft-day. A WAO process was periodically run using the sludges from both the test and control systems. The WAO was performed at various temperatures (100, 225, 250, and 275°C), pressures (2,000-2,100 psi), and sludge concentrations (2.7%, 5.0%, 7.0% and 9.0%).

The project had three major phases. In all phases the test and control systems were run for three months after achieving steady-state conditions. The test system was compared to the control system to determine whether the multiple stage system was more efficient at reducing organics and solids. The SRT of both digestion systems was 15, 9, and 20 days for phases I, II and III respectively. WAO was used after the single stage and multiple stage systems during all phases for further sludge destruction.

INFLUENT FEED SLUDGE COMPOSITION

The influent feed sludge compositions, are reported in Tables 4, 5, and 6 for phases I, II, and III, respectively. Also, the data for daily COD, TS, and VS; organic acids; and soluble phosphorus, ammonia nitrogen and organic nitrogen concentration are plotted in

Table 4: Physical and Chemical Properties of Influent Sludge in Phase I Study

Parameters	Range	Average
1. COD, mg/l	56,030.00-81,138.80	72,105.90
2. Ammonia-N, mg/l	172.10 - 654.00	475.89
3. Soluble-P*,mg/l	7.53 - 65.43	28.93
4. COD:N:P ratio		1,000/6.59/0.40
5. Solids		
TS, mg/l	30,856.00-65,672.00	49,812.90
VS, mg/l	20,888.00-44,178.00	34,402.50
VS/TS ratio		0.691
6. pH	5.20 - 6.60	5.48
7. Alkalinity as $CaCO_3$, mg/l	0.0 - 1,025.0	274.70
8. Lipids		
mg/l	6,911.40-15,861.00	11,830.60
as % of TS	22.39 - 24.15	23.75
9. Nitrogen		
NO_2, mg/l	15.12 - 61.31	26.75
NO_3, mg/l	3.50 - 38.68	12.43
Protein, mg/l	12,800.00-30,800.00	19,130.00(38.4% as TS)
Organic-N, mg/l	1,433.32-2,870.00	2,009.24
10. Carbohydrate		
mg/l	6,800.00-22,200.00	11,655.00
as % of TS	22.03 - 33.80	23.39
11. Organic Acids, mg/l		
Acetic	460.00 - 2,850.00	1,454.20
Propionic	604.50 - 1,638.00	1,638.00
Butyric	220.00 - 1,425.00	599.56
12. ORP, -mv	153.00 - 389.00	247.90
13. Conductivity, mmhos/cm	3.08 - 17.40	5.53
14. Temperature, ^{o}C	21.00 - 26.00	23.80

* Soluble portion only (No solids included)

Table 5: Physical and Chemical Properties of Influent Sludge in Phase II Study

Parameters	Range	Average
1. COD, mg/l	60,524.00-79,439.00	71,444.00
2. Ammonia-N, mg/l	246.47 - 817.85	457.02
3. Soluble-P*,mg/l	10.07 - 73.18	43.21
4. COD:N:P ratio		1,000/6.39/0.61
5. •Solids		
TS, mg/l	39,919.00-67,257.00	51,555.00
VS, mg/l	25,650.00-39,922.00	33,410.00
VS/TS ratio		0.648
6. pH	5.73 - 6.70	5.92
7. Alkalinity as $CaCO_3$, mg/l	0.0 - 688.00	212.79
8. Lipids		
mg/l	7,202.00-13,244.00	9,855.00
as % of TS	18.04 - 19.69	19.12
9. Nitrogen		
NO_2, mg/l	4.98 - 75.12	27.72
NO_3, mg/l	6.03 - 21.64	8.40
Protein, mg/l	12,600.00-30,000.00	22,385.00(43.41% as TS)
Organic-N, mg/l	1,106.15-2,242.67	1,578.20
10. Carbohydrate		
mg/l	8,500.00-20,300.00	13,985.00
as % of TS	21.29 - 30.18	27.12
11. Organic Acids, mg/l		
Acetic	360.00 - 2,200.00	1,304.00
Propionic	428.00 - 1,648.00	949.48
Butyric	280.00 - 1,138.00	673.22
12. ORP, -mv	156.00 - 457.00	339.70
13. Conductivity, mmhos/cm	1.56 - 12.80	6.47
14. Temperature, ^{o}C	23.00 - 27.00	25.02

Table 6: Physical and Chemical Proterties of Influent Sludge in Phase III study

Parameters	Range	Average
1. COD, mg/l	44,319.00-77,846.00	61,714.00
2. Ammonia-N, mg/l	96.70 - 513.91	310.17
3. Soluble-P*,mg/l	14.64 - 47.89	27.43
4. COD:N:P ratio		1,000/5.03/0.44
5. Solids		
TS, mg/l	34,244.00-65,491.00	50,419.50
VS, mg/l	20,206.00-37,124.00	28,800.00
VS/TS ratio		0.571
6. pH	5.26 - 6.72	6.03
7. Alkalinity as $CaCO_3$, mg/l	0.0 - 688.00	253.70
8. Lipids		
mg/l	3,203.00-9,529.00	6,070.50
as % of TS	9.35 - 14.55	12.04
9. Nitrogen		
NO_2, mg/l	26.54 - 106.53	64.51
NO_3, mg/l	2.29 - 14.95	4.53
Protein, mg/l	12,100.00-35,150.00	25,573.50(50.72% as TS)
Organic-N, mg/l	1,178.20-2,295.00	1,732.70
10. Carbohydrate		
mg/l	5,075.00-18,000.00	9,726.50
as % of TS	14.82 - 27.48	19.29
11. Organic Acids, mg/l		
Acetic	180.00 - 1,363.00	818.905
Propionic	174.00 - 1,272.00	643.00
Butyric	41.00 - 738.00	245.18
12. ORP, -mv	180.00 - 316.00	208.34
13. Conductivity, mmhos/cm	2.22 - 7.97	3.81
14. Temperature, ^{o}C	22.00 - 25.00	23.30

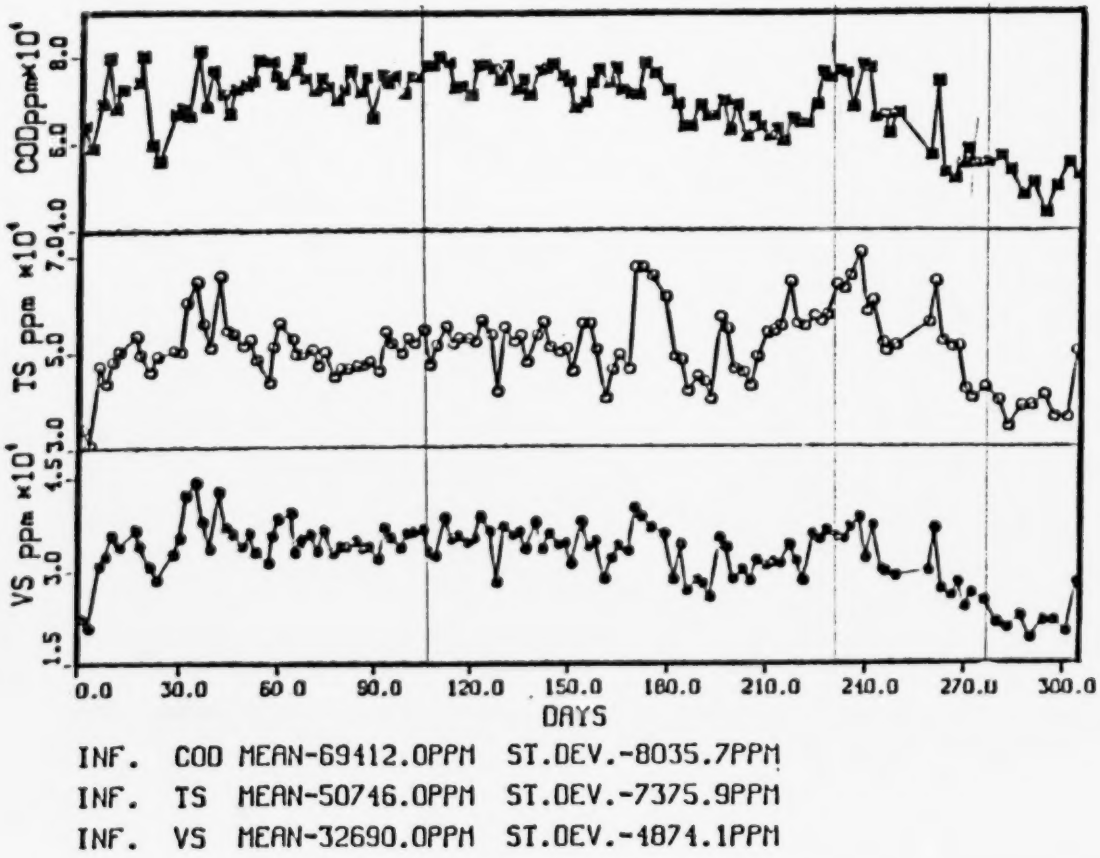


Figure 5: Influent Daily COD, VS, and TS Concentration

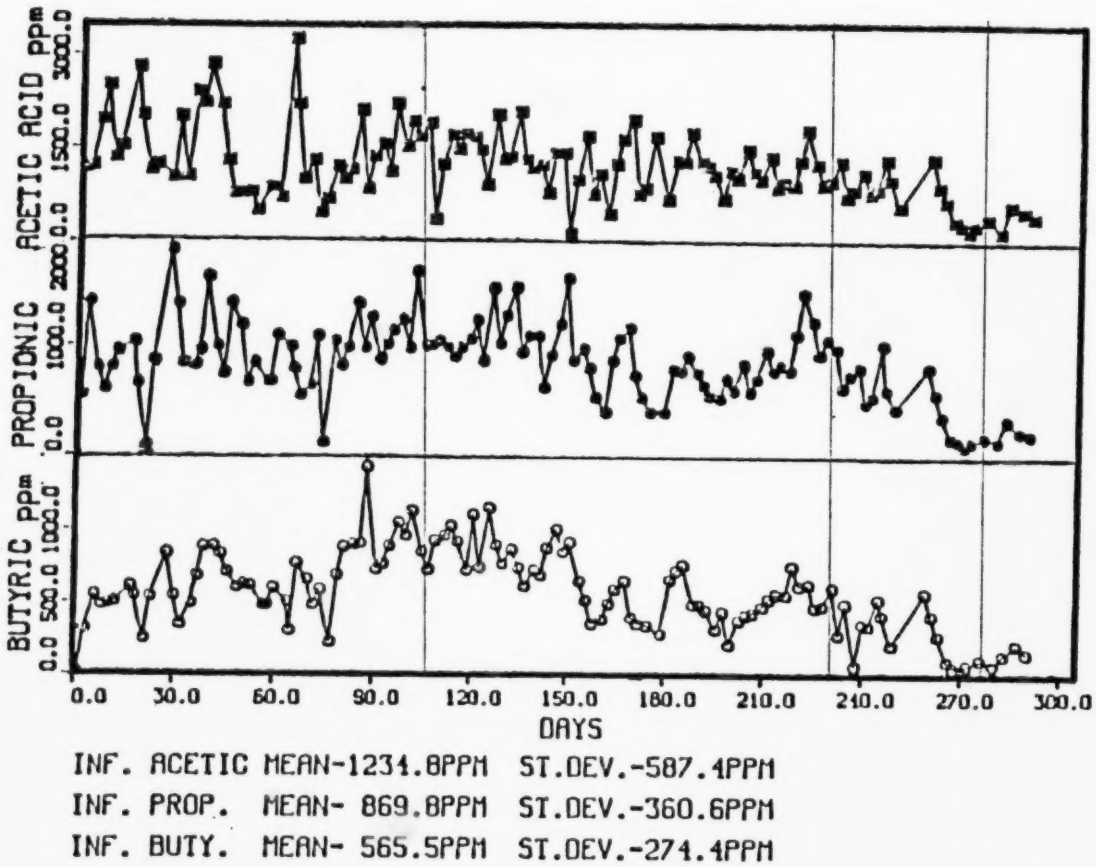


Figure 6: Influent Daily Organic Acids Concentration

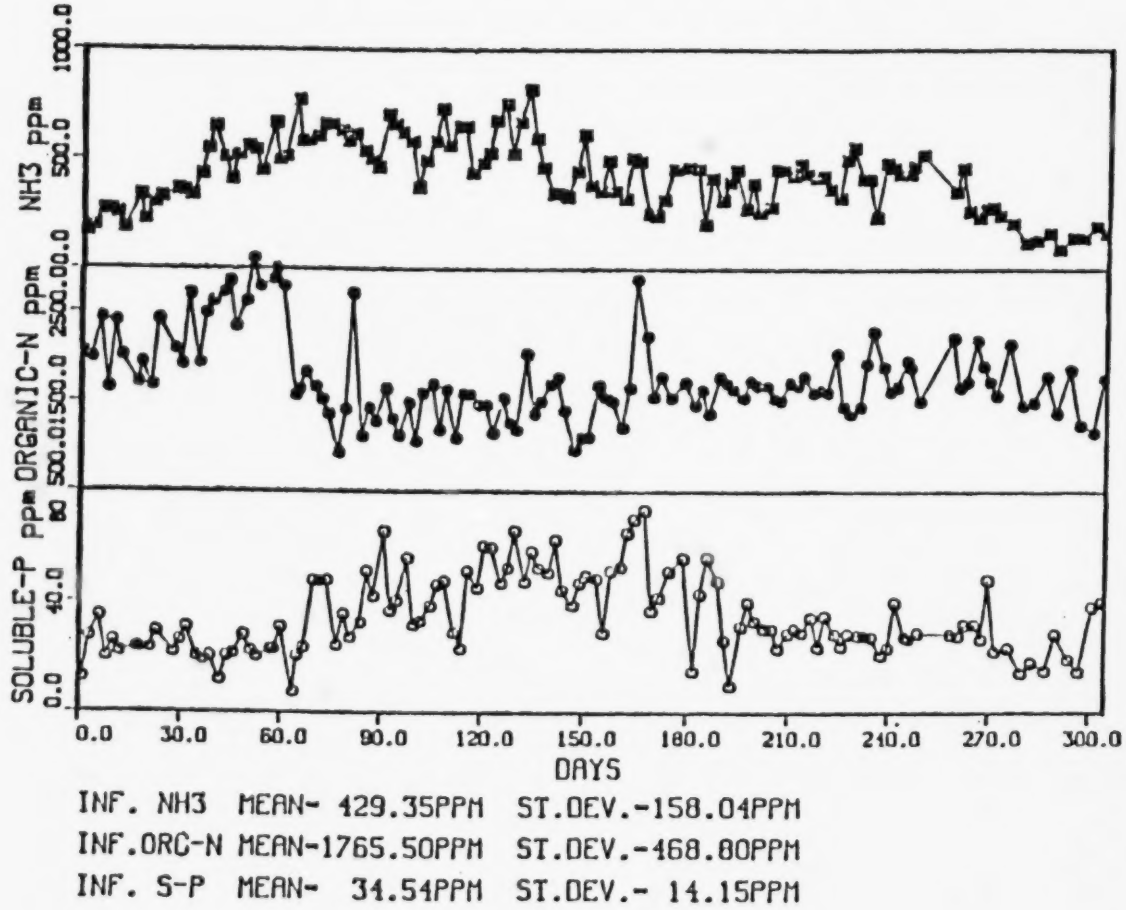


Figure 7: Influent Daily Soluble Phosphorus, , Ammonia Nitrogen, and Organic Nitrogen Concentration

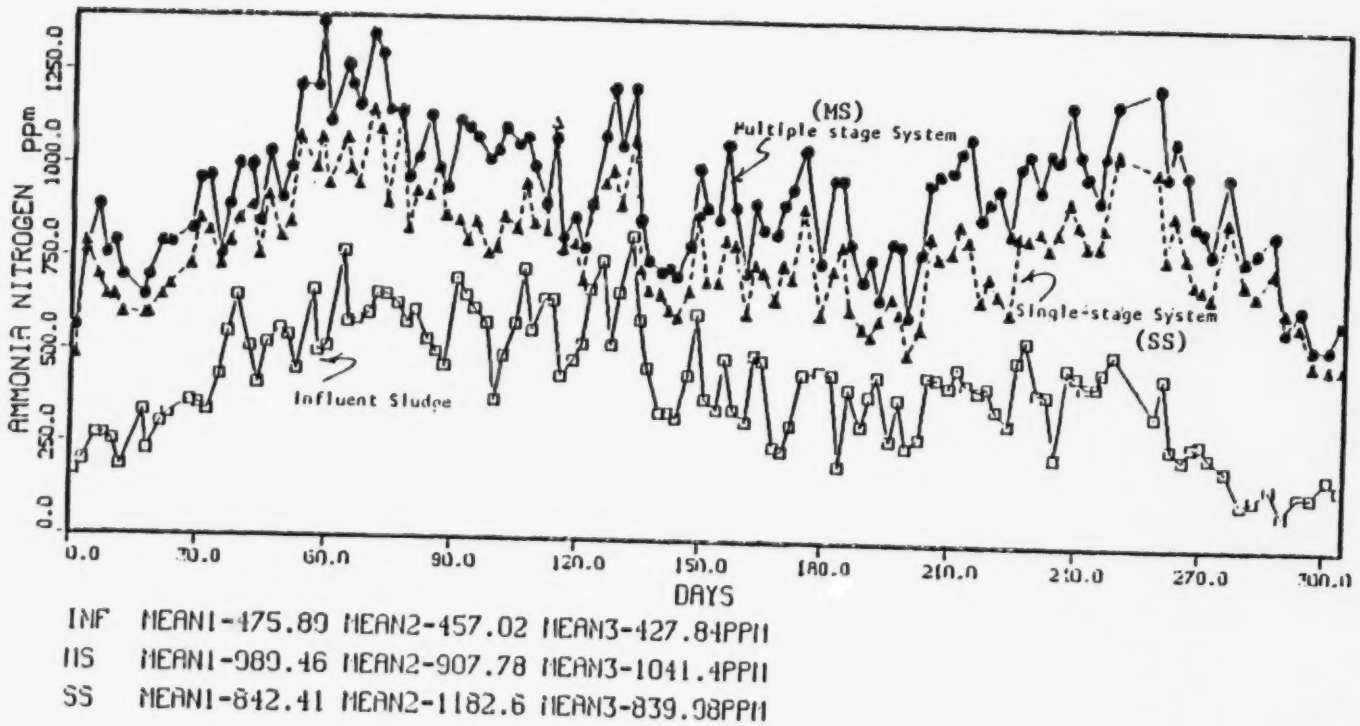


Figure 8: Influent and Effluent Ammonia Nitrogen Concentration in the Single-stage System and the Multiple-stage System at Phases I, II, and III

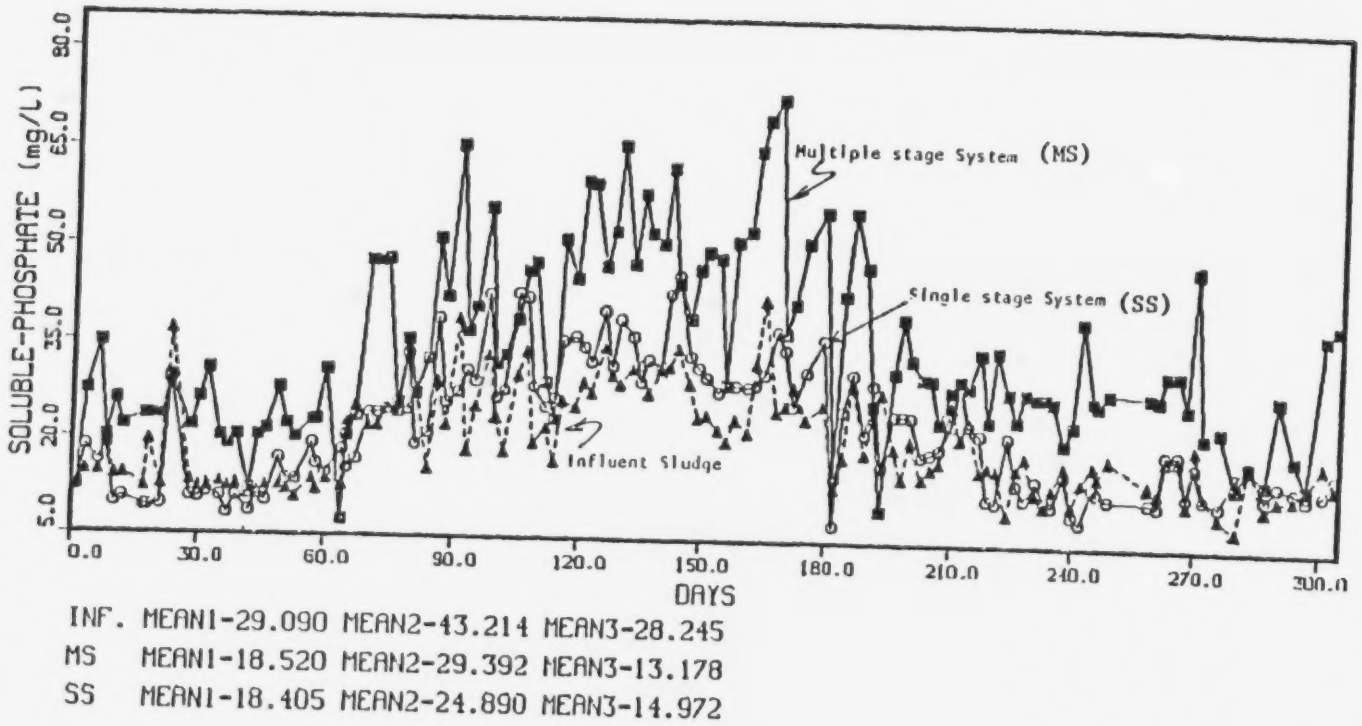


Figure 9: Influent and Effluent Soluble Phosphorus Concentration in the Single-Stage System and the Multiple-stage System at Phases I, II, and III

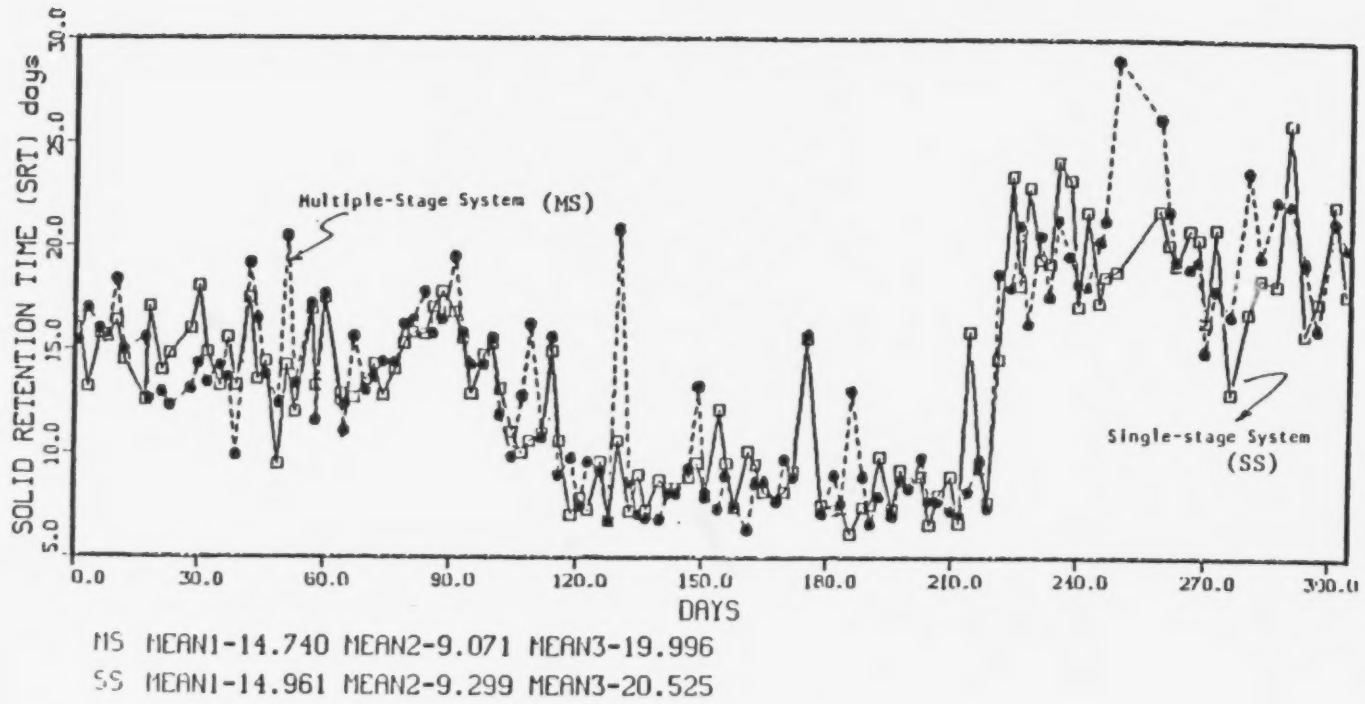


Figure 10: Solids Retention Time in the Single-stage System and the Multiple-stage System at Phases I, II, and III

Figures 5, 6, and 7, respectively.

The influent sludge generally had the following characteristics: acidic; high in COD/N/P ratio, organic acids and ORP; and low in VS/TS ratio, alkalinity and conductivity as compared to waste activated sludge. As a percent of total solids (TS) the contents of lipid, protein, and carbohydrate averaged from 12.04 to 23.75%, 38.40 to 50.72%, and 19.29 to 27.12%, respectively. The average solids content of the influent sludge ranged from 4.98 to 5.15% as TS and from 2.88 to 3.44% as VS. Nitrogen and phosphorus concentrations are shown in Figures 8 and 9.

SOLIDS RETENTION TIME (SRT)

This study used three target SRTs of 15, 9, and 20 days for Phase I, II, and III, respectively. The actual average SRT values were as shown in Table 7.

The SRT data are depicted in Figure 10, which shows that, in both systems, SRT varied daily as a result of small changes in the influent feed rate caused by pump control problems. The Phase III study was performed at two first-stage SRTs without significantly changing the overall SRT of approximately 20 days. This change was made to eliminate a foaming problem in the first stage.

Table 7: Individual and Overall SRTs

Phase	Duration of experiment	No. of Samples	Multiple stage System				Single stage System
			Stage 1	Stage 2	Stage 3	Overall	
I	100 days	42	1.63	8.17	4.90	14.73	15.00
II	117 days	50	1.00	5.03	3.02	9.07	9.29
III	88 days	15	2.22	11.10	6.66	19.99	20.52
		14	1.48	11.11	6.65	19.25	19.26

DIGESTION TEMPERATURE, CONDUCTIVITY, pH, ALKALINITY, AND OXIDATION-REDUCTION POTENTIAL

The variation of digestion temperature in the single stage system and the multiple stage system is shown in Figure 11. The mean temperatures were 35.5°C in the single stage system and 35.4°C, 35.5°C, and 49.3°C in the first, second, and third stage of the multiple stage system, respectively. The influent sludge temperature was nearly equal to the room temperature of 24.2°C. Temperatures were fairly contant except for the third stage and single stage digesters, which experienced some temperature control problems.

The mean alkalinity, pH, ORP, and conductivity values in the multiple stage and single stage systems are shown in Table 8.

The conductivity in the multiple-stage system gradually increased with stage order but decreased with an increase in digester SRT. Also, the conductivity in the final stage of the multiple-stage system was greater than that of the single-stage system. These results indicated that the third stage apparently had more ionic solutes than the first and second stages, or the single stage system.

It can be seen in Table 8 that the staging influence on ORP, pH and alkalinity was the same as on conductivity; that is the values increased as the digested sludge passed through each subsequent stage. The third stage digester pH and ORP were higher, and the alkalinity was lower than those of the single stage system.

Table 8 shows that the physical and chemical properties of digested sludge changes because of the staging effect, especially in the first and second digesters. It appears that the reactions of hydrolysis - acidification, acidificiation - methanation, and methanation can be isolated by staging. This was why the pH and alkalinity were the lowest in the first stage, and rose as a result of the conversion of organic acids and hydrogen to methane and carbon dioxide in the second and third stages. Also, as more ionic substances/compounds were formed in each stage, the digester contents became more reduced. More importantly, this study showed that the separation of the digestion

Table 8: Mean Values of Alkalinity, pH, ORP, and Conductivity in the Single Stage and Multiple Stage Systems

Parameter	Feed	Multiple-stage System Stage 1	Stage 2	Stage 3	Single-stage System
Alkalinity as $CaCO_3$, mg/l					
Phase I	274.7	67.57	3463.30	4443.60	4872.10
Phase II	212.8	64.44	4158.80	4716.50	4742.80
Phase III	212.8	237.00	4422.70	4566.20	4609.50
pH					
Phase I	5.67	5.46	7.38	7.74	7.57
Phase II	5.91	5.60	7.54	7.84	7.62
Phase III	5.91	6.33	7.59	7.89	7.58
ORP, -mv					
Phase I	247.80	227.93	271.41	278.22	268.42
Phase II	339.71	337.92	400.05	407.71	407.40
Phase III	174.31	236.22	289.42	309.23	288.91
Conductivity, mmhos/cm					
Phase I	5.69	8.63	12.92	17.22	15.48
Phase II	6.46	8.79	13.53	18.60	16.46
Phase III	3.75	7.62	12.19	13.91	9.25

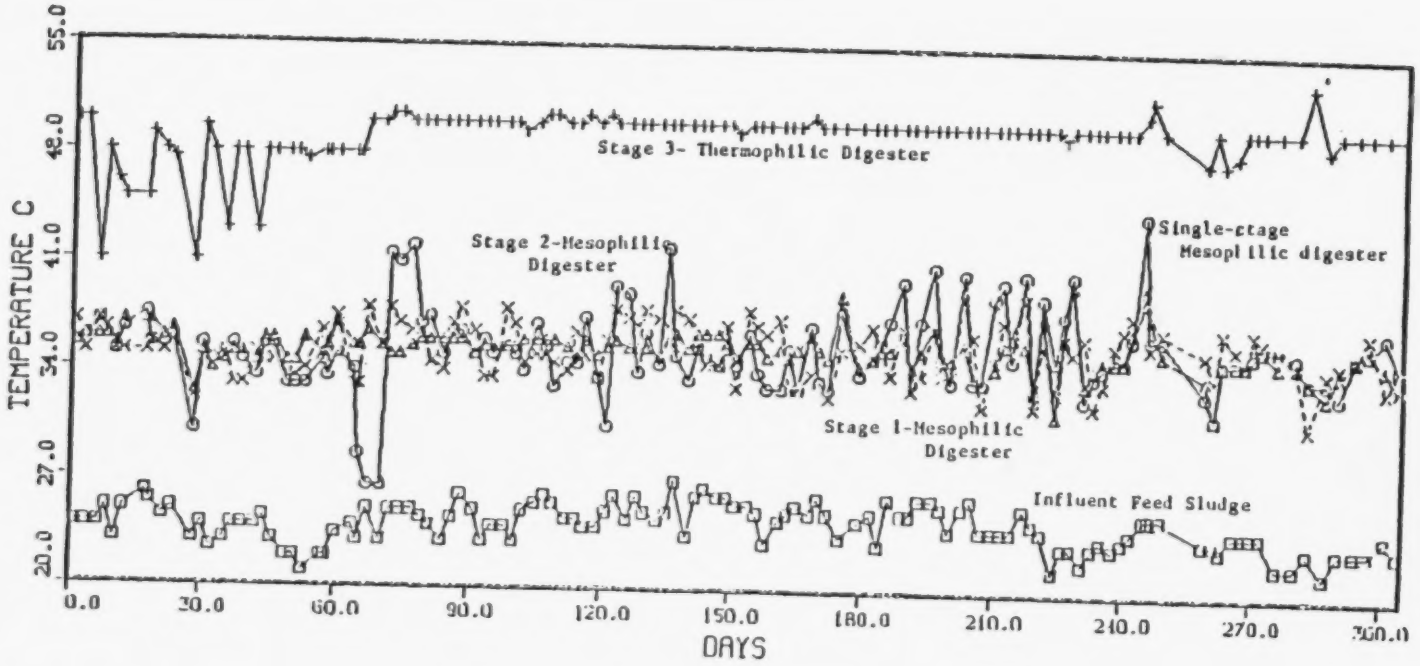


Figure 11: Digestion Temperature in the Single-stage System and the Multiple-stage System

reactions did not create a need for the addition of external additives to control alkalinity and pH.

DIGESTION EFFICIENCY AS A FUNCTION OF LOADING CONDITION

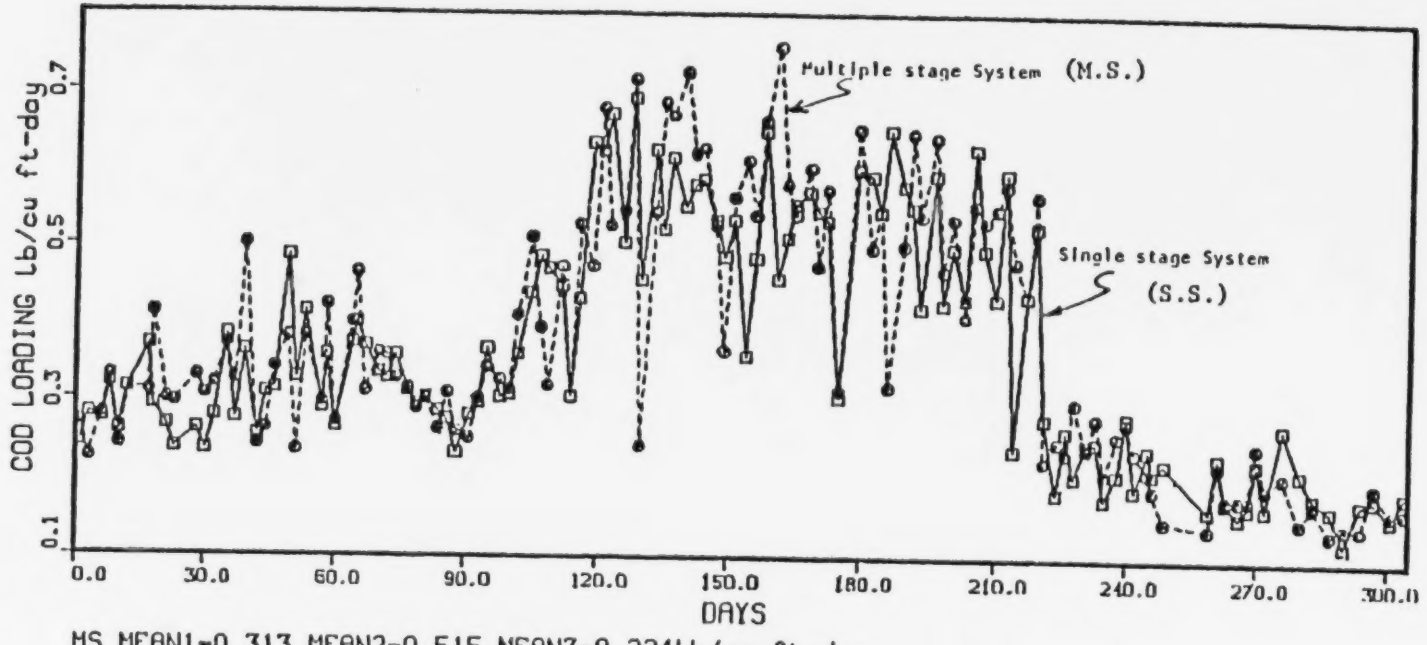
Multiple Stage System

The COD, VS, and acetic acid loadings to the single stage system, to the overall multiple stage system, and to each stage of the multiple stage digestion system are shown in Figures 12 through 17. The average COD and VS concentrations and loadings for each Phase are reported in Table 9. As shown in Figure 16, the mean acetic acid loadings (MAAL) were equal to 0.0063, 0.0093, 0.0035, and 0.0019 lb/cu ft-day, respectively, at Phases I, II, III-(a) and III-(b) in both systems. As shown in Figure 17, the mean MAAL in each stage of the multiple stage system were, respectively, 0.0563, 0.0148, and 0.0060 lb/cu ft-day for Phase I; 0.0837, 0.0222, and 0.0108 lb/cu ft-day for Phase II; 0.0312, 0.0050, and 0.0011 lb/cu ft-day for Phase III-(a); and 0.0251, 0.0030, and 0.0009 lb/cu ft-day for Phase III-(b).

The daily variations of loading shown in Figures 12 through 17 were due to the inherent variability of the influent sludge concentration and feed rate control problems. However, the applied COD, VS, and acetic acid loadings were similar for both systems in each Phase of the investigation.

For all Phases of the study, as can be seen in Table 9 and Figures 18 and 19, the multiple stage system was superior to the single stage system in terms of COD and VS destruction. The total COD removal in the multiple stage system was 59% in Phase I, 44% in Phase II, 54% in Phase III-(a), and 56% in Phase III-(b). For the control system, the COD reduction was 42%, 32%, 44% and 38%, respectively, for Phase I, II, III-(a) and III-(b). The VS destruction by the single stage system, as compared to the multiple stage system, was 50% vs 67%, 44% vs 60%, 49% vs 59%, and 46% vs 62%, respectively, in the Phase I, II, III-(a) and III-(b) investigations.

The data shown in Table 9 and Figures 20 and 21 indicate the greatest destruction of COD and VS consistently occurred in the second stage of multiple stage digestion system. The third stage digester removed more COD and VS than the first stage digester



MS MEAN1-0.313 MEAN2-0.515 MEAN3-0.224lb/cu ft-day

SS MEAN1-0.310 MEAN2-0.512 MEAN3-0.221lb/cu ft-day

Figure 12: COD Loading to the Single stage System and the Multiple stage System at Phases I, II, and III

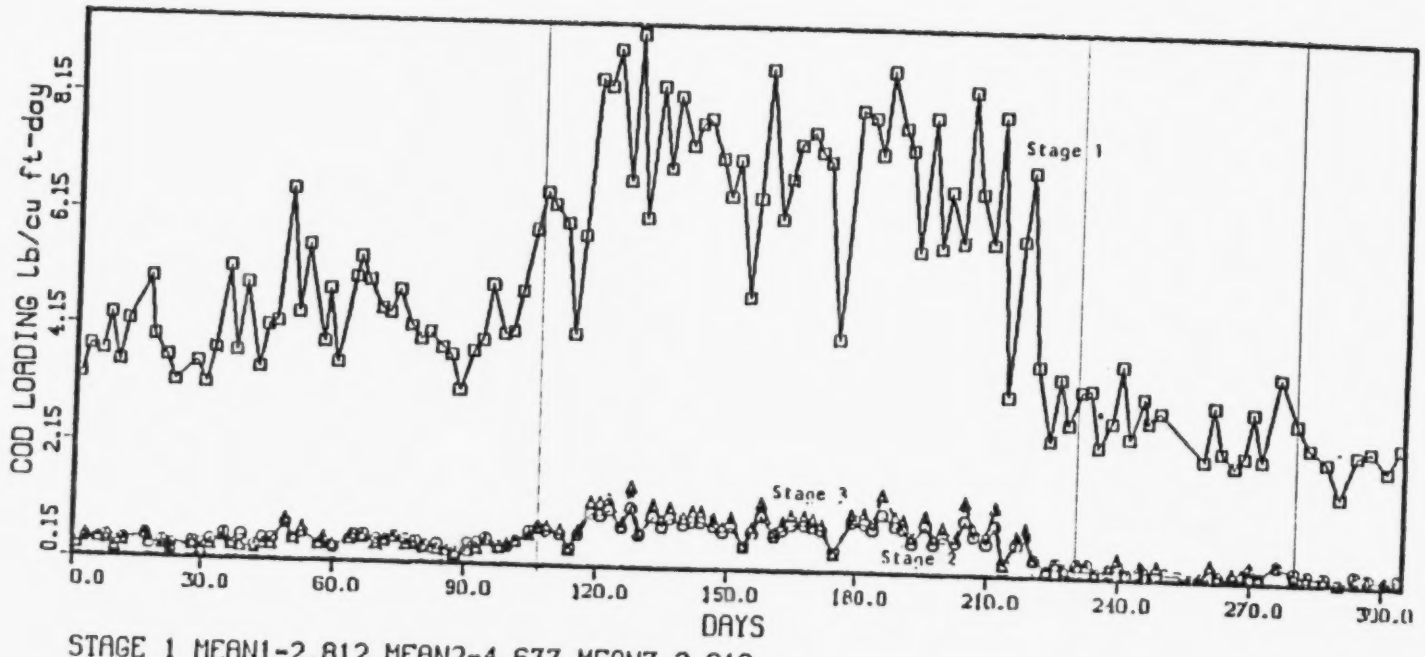


Figure 13: COD Loading to Each Stage of the Multiple-stage System at Phases I, II, and III

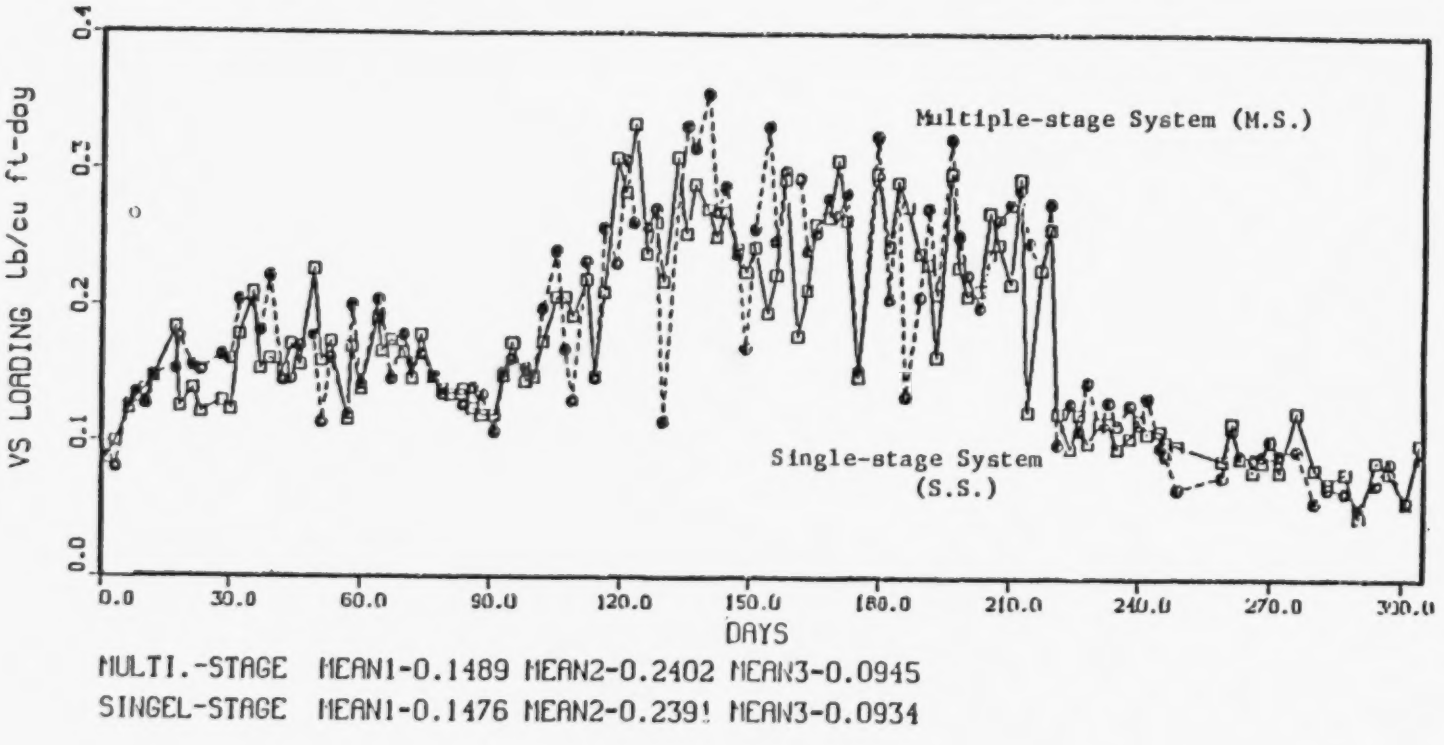


Figure 14: VS Loading to the Single-stage System and the Multiple-stage System at Phases I, II, and III

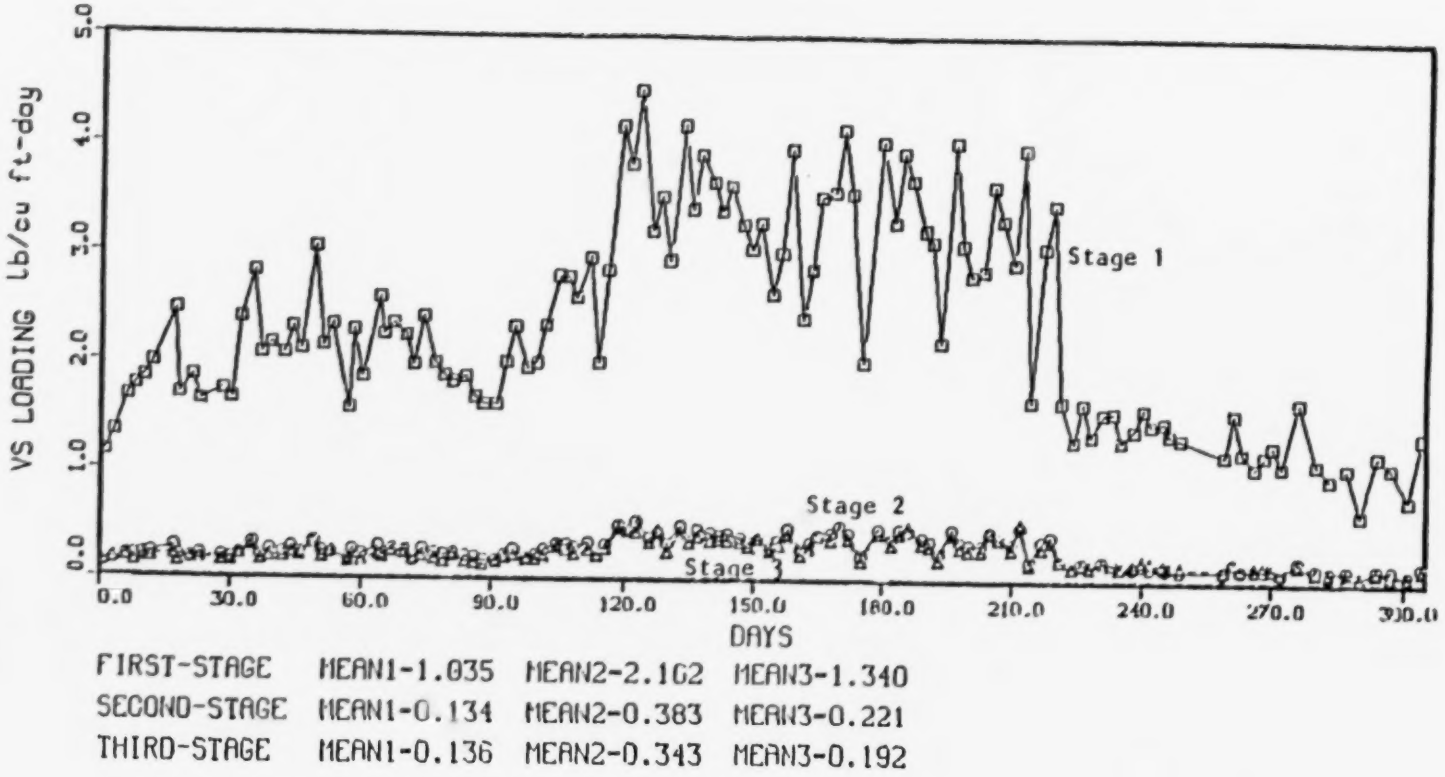


Figure 15: VS Loading to Each Stage of the Multiple-stage System at Phases I, II, and III

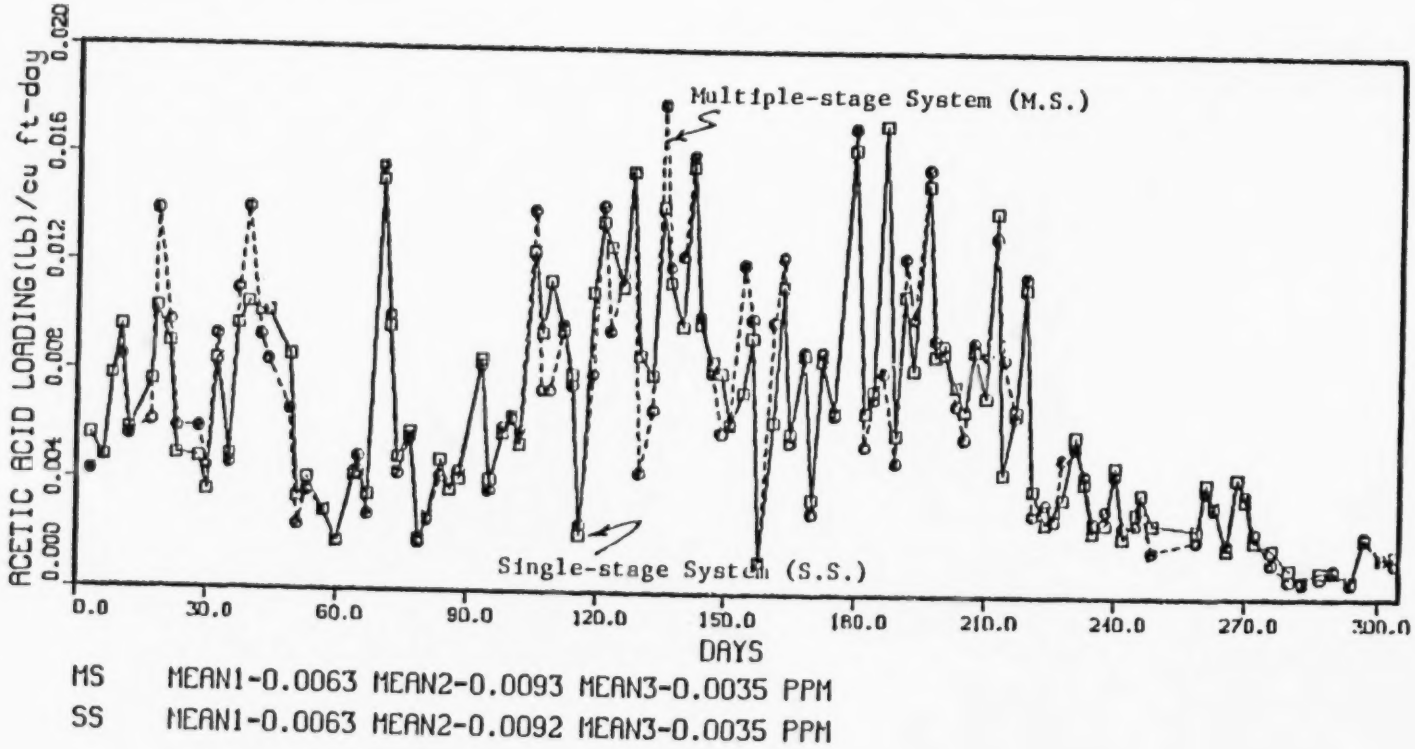


Figure 16: Acetic Acid Loading to the Single-stage System and the Multiple-stage System at Phases I, II, and III

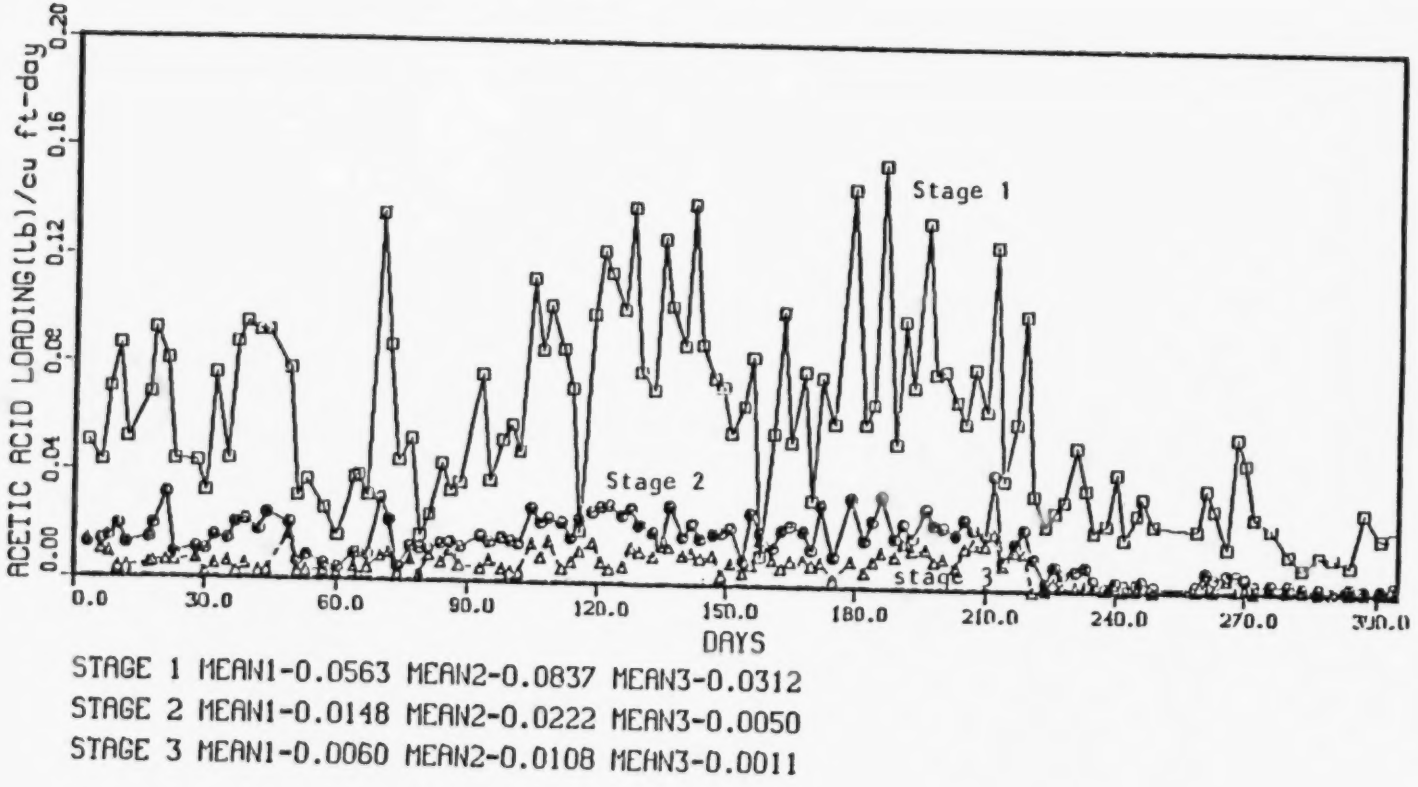


Figure 17: Acetic Acid Loading to Each Stage of the Multiple-stage System at Phases I, II, and III

Table 9. Average COD and VS Loadings and Reductions Through Each Stage of the Three-Stage System and the Single-Stage System

Phase	Overall SRT, days	COD/VS	Parameter	Feed	Multiple-Stage System Stage 1	Stage 2	Stage 3	Overall	Single-Stage System
I	MS:14.735 * SS:15.000	COD	Conc., mg/L	72106.0	62970.0	35474.0	29417.0	---	41984.0
			Loading**		2.812	0.492	0.463	0.312	0.310
			Reduction %		12.524	43.532	17.039	59.235	41.762
II	MS: 9.071 SS: 9.299	COD	Conc., mg/L	71444.0	64917.0	44682.0	40114.0	---	48852.0
			Loading		4.637	0.846	0.983	0.515	0.512
			Reduction %		9.113	31.172	10.395	43.751	31.571
III (a)	MS:19.996 SS:20.525	COD	Conc., mg/L	70271.0	56308.0	37521.0	32395.0	---	39619.0
			Loading		2.019	0.323	0.361	0.224	0.220
			Reduction %		20.178	32.505	13.456	53.860	43.534
(b)	MS:19.258 SS:19.264	COD	Conc., mg/L	53157.0	46199.0	28468.0	23719.0	---	33067.0
			Loading		2.465	0.288	0.294	0.183	0.176
			Reduction %		12.906	38.197	16.998	55.539	37.703
I	MS:14.735 SS:15.000	VS	Conc., mg/L	34402.0	28590.0	14736.0	11187.3	---	16856.8
			Loading		1.035	0.134	0.221	0.149	0.148
			Reduction %		11.522	48.457	24.083	67.480	51.000
II	MS: 9.071 SS: 9.299	VS	Conc., mg/L	33410.0	29445.0	15725.0	13213.0	---	18759.0
			Loading		2.162	0.383	0.192	0.240	0.239
			Reduction %		11.867	46.595	15.974	60.451	43.852
III (a)	MS:19.996 SS:20.525	VS	Conc., mg/L	33768.0	25474.0	16447.0	13755.0	---	17077.0
			Loading		0.962	0.145	0.157	0.107	0.106
			Reduction %		24.850	34.380	16.150	59.266	49.428
(b)	MS:19.258 SS:19.264	VS	Conc., mg/L	23832.0	19566.0	11175.0	9045.9	---	12731.0
			Loading		1.108	0.122	0.115	0.0820	0.0791
			Reduction %		17.740	43.130	19.680	62.043	46.580

* MS = Multiple-Stage, SS = Single-Stage.

** Loading: lb COD or VS / cuft-day.

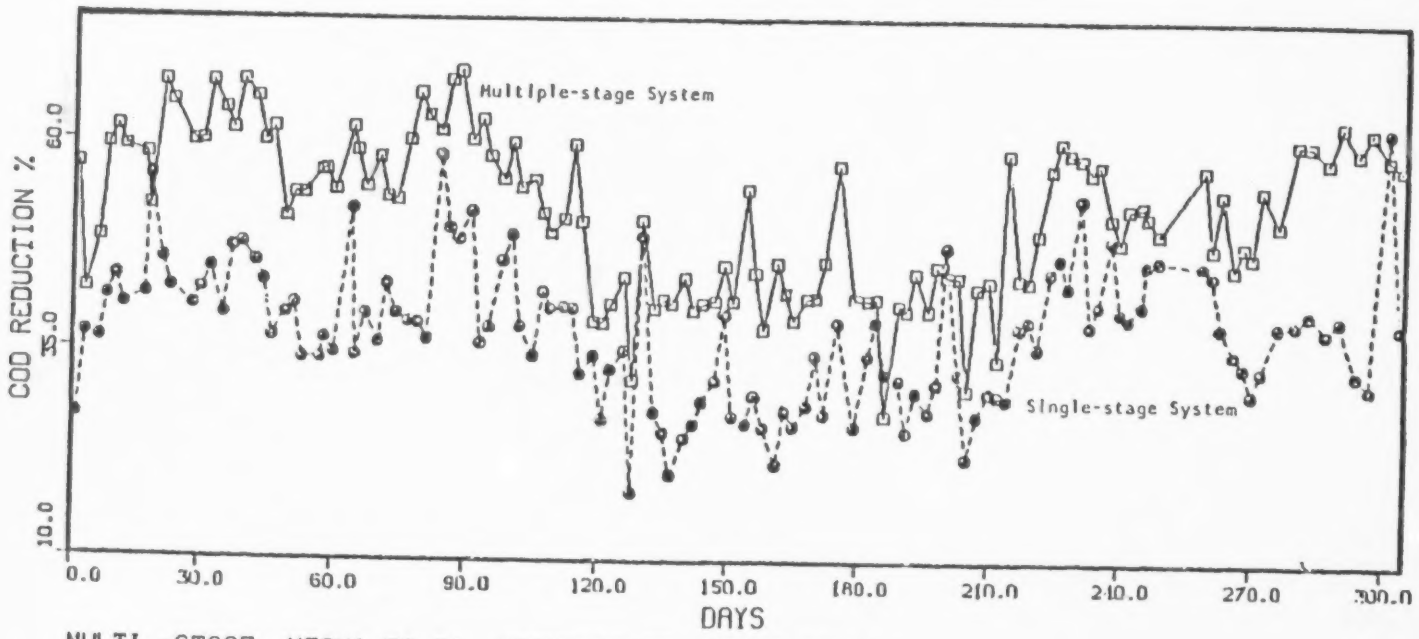


Figure 18: Percent COD Reduction in the Single-stage System and the Multiple-stage System at Phases I, II, and III

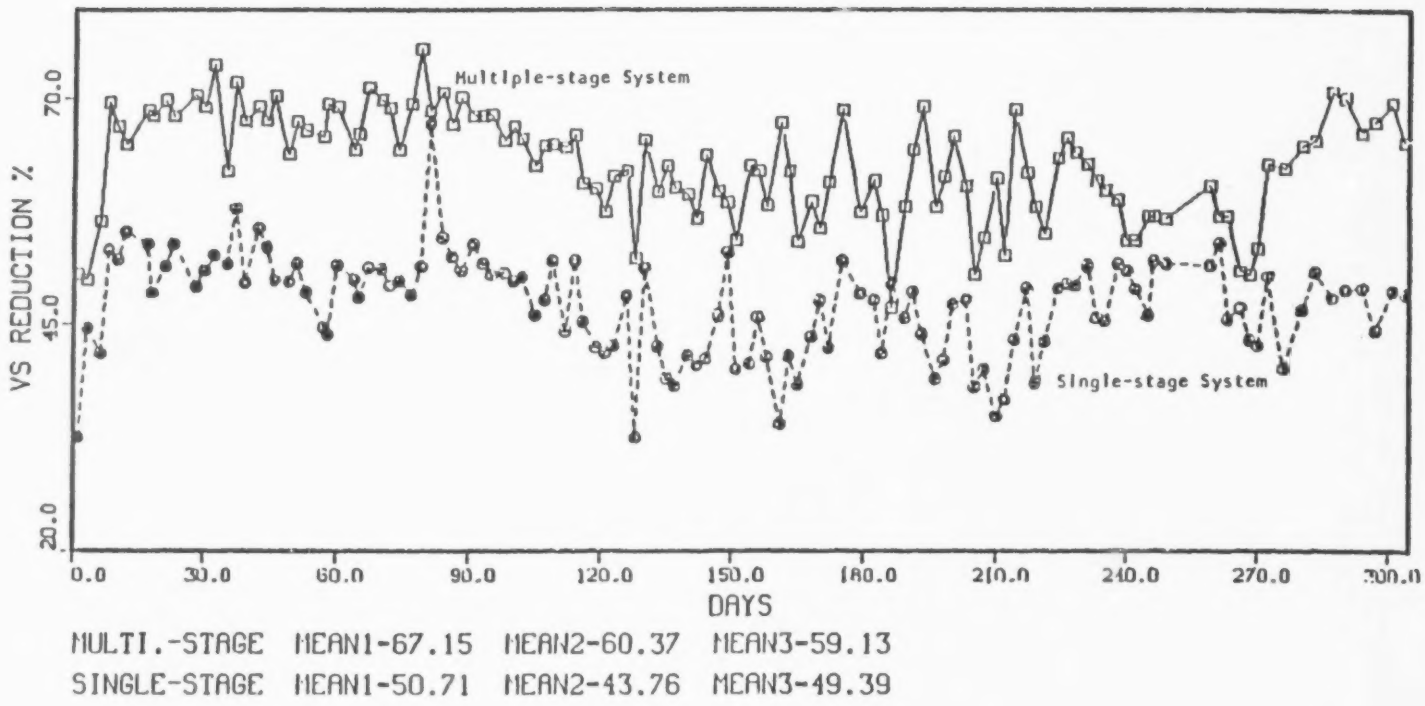


Figure 19: Percent VS Reduction in the Single-stage System and the Multiple-stage System at Phases I, II, and III

except during Phase III-(a). Phase III-(a) was also the only phase during which gas production was greater in the first stage than in the third stage.

Although the SRT was the longest in Phase III, the overall efficiency of COD and VS removal was not the highest. This may indicate that the SRT of each stage of the multiple stage system was not at an optimum. Particularly, a first stage SRT equal to 2.222 days produced a serious problem of foaming in the first stage, which could be primarily the result of too long of a solids retention time. The foaming problem was reduced as a result of decreasing the SRT to 1.389 days. It appears that in order to prevent the digester from foaming, the first digester SRT has to be about 1.0 days. The digestion efficiency of the second and third stages was adversely affected when the foaming occured in the first stage of the multiple stage system. The same problem was observed in the single stage system at all SRTs, particularly at a shorter solids retention time. Further investigation on this matter should be conducted in future work.

To highlight the efficiency of staging, a summary of the performance of the first two stages of the multiple stage system is shown in Table 10. It is evident from Table 10 that the first two stages alone were more efficient in removing COD and VS than the single stage system even though the loadings were higher for the two stages of the multiple stage system.

It appears from this study that the anaerobic digestion of waste sludges can be accomplished more readily when the biochemical reactions are carried out in a series of separate reactors, especially when the hydrolysis- acidification step is separated from the methanation step. In this study a 35% reduction in total digester volume along with a 2 to 9% increase in COD and VS reduction was possible.

SUBSTRATE TRANSFORMATION

Reductions of COD and VS in the multiple stage system were illustrated in Figures 20 and 21 and listed in Table 9. Figures 22 and 23 report the COD and VS concentration profile for each stage of the multiple stage system. It is apparent from these figures that the maximum COD and VS reductions occured in the second stage.

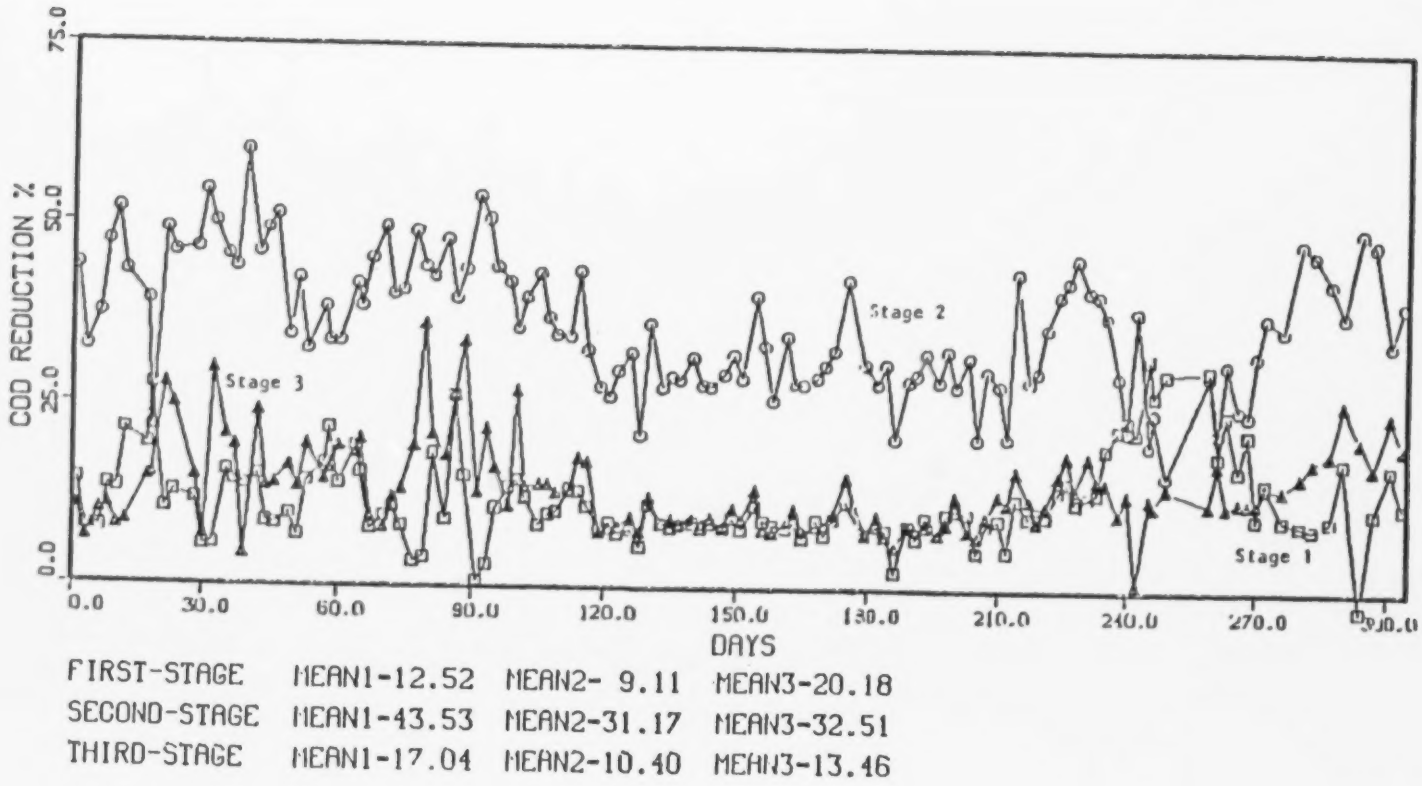
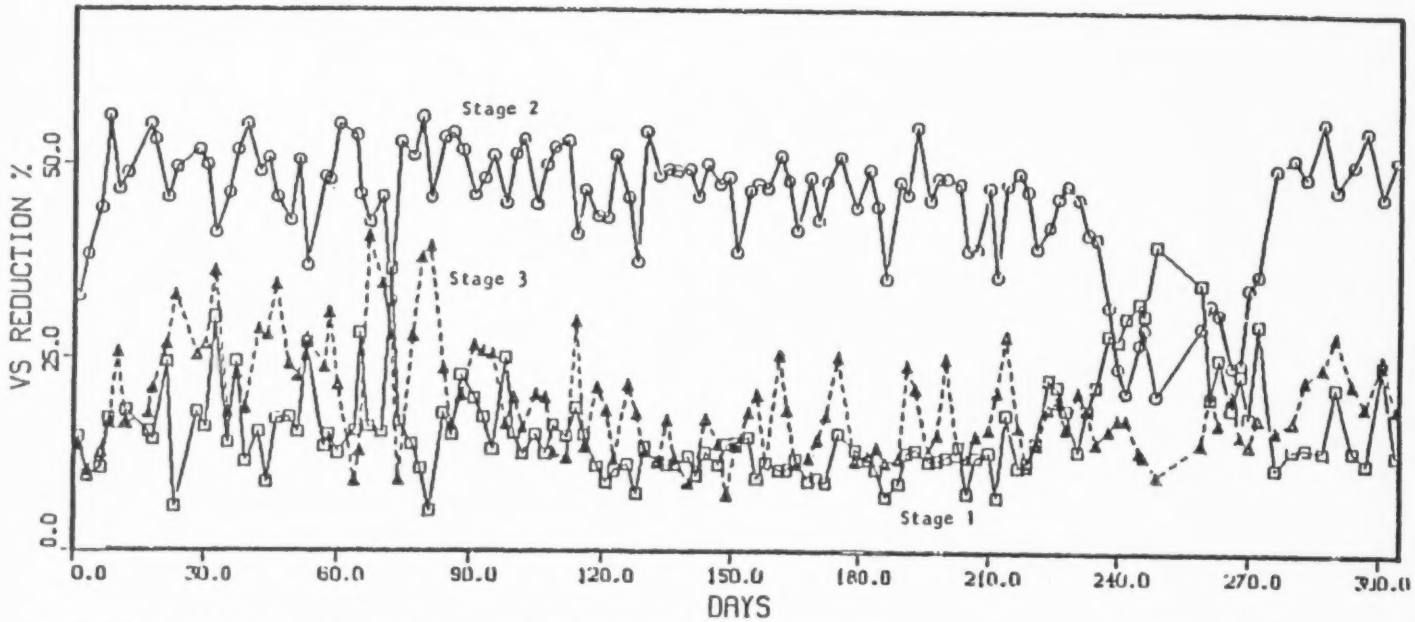


Figure 20: Percent COD Reduction in Each Stage of the Multiple-stage System at Phases I, II, and III



FIRST-STAGE	MEAN1-16.78	MEAN2-11.81	MEAN3-24.85
SECOND-STAGE	MEAN1-48.02	MEAN2-46.53	MEAN3-34.39
THIRD-STAGE	MEAN1-23.70	MEAN2-16.07	MEAN3-16.15

Figure 21: Percent VS Reduction in Each Stage of the Multiple-stage System at Phases I, II, and III

Table 10. Average COD and VS Concentrations and Reductions Through Each Stage of the Two-Stage System and the Single-Stage System

Phase	Overall SRT, days	COD/VS	Parameter	Feed	Two-Stage System Stage 1	Two-Stage System Stage 2	Two-Stage System Overall	Single-Stage System
I	TS: 9.826 * SS:15.000	COD	Conc., mg/L	72106.0	62970.0	35474.0	---	41984.0
			Loading**		2.812	0.492	0.468	0.310
			Reduction %		12.524	43.532	50.821	41.762
II	TS: 6.047 SS: 9.299	COD	Conc., mg/L	71444.0	64917.0	44682.0	---	48852.0
			Loading		4.637	0.846	0.772	0.512
			Reduction %		9.113	31.172	37.362	31.571
III (a)	TS:13.331 SS:20.525	COD	Conc., mg/L	70271.0	56308.0	37521.0	---	39619.0
			Loading		2.019	0.323	0.336	0.220
			Reduction %		20.178	32.505	46.649	43.534
(b)	TS:11.912 SS:19.264	COD	Conc., mg/L	53157.0	46199.0	28468.0	---	33067.0
			Loading		2.465	0.288	0.557	0.176
			Reduction %		12.906	38.197	44.248	37.703
I	TS: 9.826 SS:15.000	VS	Conc., mg/L	34402.0	28590.0	14736.0	---	16856.8
			Loading		1.035	0.134	0.223	0.148
			Reduction %		11.522	48.457	56.882	51.000
II	TS: 6.047 SS: 9.299	VS	Conc., mg/L	33410.0	29445.0	15725.0	---	18759.0
			Loading		2.162	0.383	0.360	0.239
			Reduction %		11.867	46.595	52.802	43.852
III (a)	TS:13.331 SS:20.525	VS	Conc., mg/L	33768.0	25474.0	16447.0	---	17077.0
			Loading		0.962	0.145	0.160	0.106
			Reduction %		24.850	34.380	51.255	49.428
(b)	TS:11.912 SS:19.264	VS	Conc., mg/L	23832.0	19566.0	11175.0	---	12731.0
			Loading		1.108	0.122	0.261	0.0791
			Reduction %		17.740	43.130	54.120	46.580

* TS = Two-Stage, SS = Single-Stage.

** Loading: lb COD or VS / cuft-day.

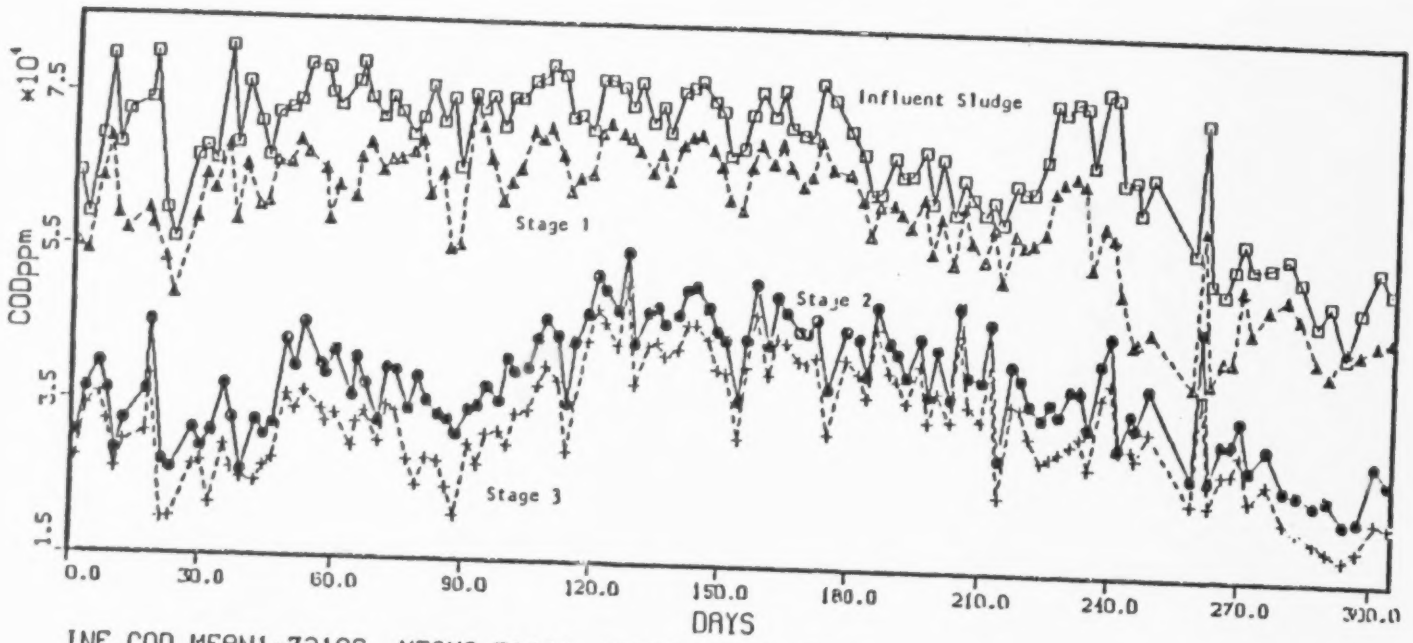
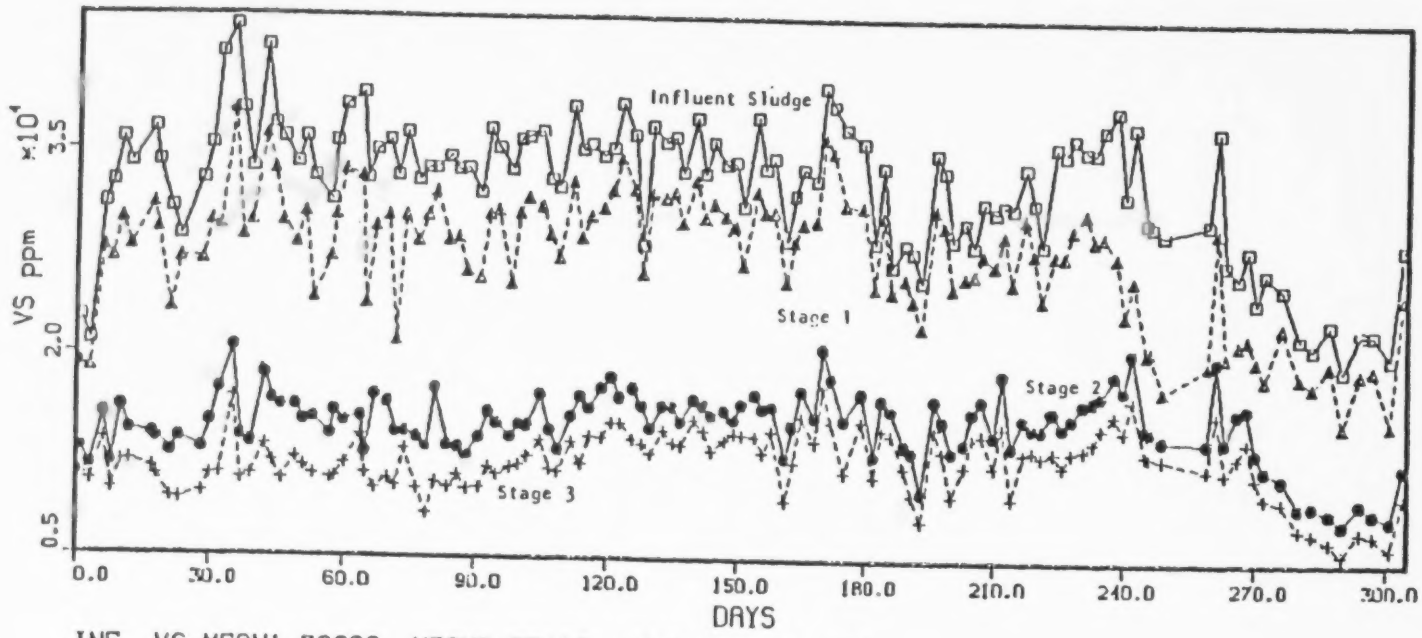


Figure 22: COD Concentration Profile In Each Stage of the Multiple-stage System at Phases I, II, and III



INF. VS MEAN1-32690. MEAN2-33410. MEAN3-33768. PPM
STAGE 1 MEAN1-28590. MEAN2-29445. MEAN3-25474. PPM
STAGE 2 MEAN1-14737. MEAN2-15725. MEAN3-16447. PPM
STAGE 3 MEAN1-11187. MEAN2-13213. MEAN3-13755. PPM

Figure 23: VS Concentration Profile In Each Stage of the Multiple-stage System at Phases I, II, and III

The mean concentrations of volatile acids(acetic, propionic, and butyric), lipids, proteins, and carbohydrates in the feed sludge and each digester are summarized in Table 11 through 14. If hydrolysis-acidification was occurring in the first stage of the multiple stage system the pH should have decreased and the concentrations of volatile acids should have increased. This was seen during Phase I and II, but not during Phase III, possibly due to the foaming problem during Phase III-(a). pH continued to rise in the successive stages of the multiple stage system as expected. SRT did not appear to have an appreciable effect on pH except in the first stage during III, as noted above.

Theoretically, if the digestion system could provide an adequate SRT, propionic acid and butyric acid would be completely converted to acetic acid by the second and third stages. The maximum rate of acetic acid utilization was by methane-producing bacteria in the second stage mesophilic digester; this methanation process continued in the third stage thermophilic reactor.

Several observations concerning lipid, protein, and carbohydrate destruction can be made based on Tables 11 through 14. Hydrolytic and liquefying organisms existed in all three digestion stages of the multiple stage system, as shown by the reductions of lipid, protein, and carbohydrates in all three digesters.

Lipid digestion increased as SRT increased in the first and second stages of the multiple-stage system and in the single-stage system, but only between Phases I and II. No change was seen in the third stage during Phases I and II, or in any digester between Phase I and III.

Protein digestion varied in the digesters during all of the phases, but no trend in terms of SRT was observed.

Carbohydrate digestion increased with increasing SRT in the first stage of the multiple-stage system through all the phases. Carbohydrate digestion did not appear to change in the second stage with respect to SRT, except in Phase III-(a) where it was lower, possibly due to the foaming problem in the first stage. Carbohydrate digestion increased with increasing SRT in the third stage between Phase I and II, but not between Phases I and III. Carbohydrate digestion in the single-stage system did not change between Phases I and II, but decreased with the increased SRT of Phase III.

Table 11: Digestion of Sludge Lipids, Proteins, and Carbohydrates and Production/Utilization of Organic Acids in Each Stage of the Multiple Stage System and the Single System in Phase I.

Overall SRT, days	COD* Loading	VS* Loading	Function	Parameter	Feed	Multiple-Stage System Stage 1	Stage 2	Stage 3	Overall	Single-Stage System
MS:14.735 **	0.312	0.148	Acetic Acid	Conc., mg/L	1454.20	1910.60	454.58	151.91	---	155.540
				Difference		-456.40	1456.02	302.67	---	1298.66
SS:15.000	0.310	0.147		Reduction %		-23.88	76.21	66.58	89.55	89.30
			Propionic Acid	Conc., mg/L	930.34	1461.10	541.54	142.45	---	31.570
				Difference		-530.76	919.56	399.09	---	898.770
				Reduction %		-36.32	62.93	73.69	84.68	96.60
			Butyric Acid	Conc., mg/L	599.56	885.04	176.30	26.96	---	7.513
				Difference		-285.48	708.74	149.34	---	592.047
				Reduction %		-32.25	80.07	84.71	95.50	98.74
			Lipid	Conc., mg/L	11830.6	8801.7	4729.5	3426.4	---	5123.6
				Difference		3028.9	4072.2	1303.1	---	6707.0
				Reduction %		25.60	46.46	27.55	71.03	56.69
			Protein	Conc., mg/L	19130.0	16297.0	13296.0	11130.0	---	14321.0
				Difference		2833.0	3001.0	2166.0	---	4809.0
				Reduction %		14.80	18.41	16.29	41.81	25.13
			Carbohydrate	Conc., mg/L	11655.0	8408.0	4371.0	2881.0	---	6640.0
				Difference		3247.0	4037.0	1490.0	---	5015.0
				Reduction %		27.85	48.01	34.08	75.28	43.02

* Loading: lb COD or VS / cuft-day.

** MS = Multiple-Stage, SS = Single-Stage.

Table 12: Digestion of Sludge Lipids, Proteins, and Carbohydrates and Production/Utilization of Organic Acids in Each Stage of the Multiple Stage System and the Single Stage System in Phase II.

Overall SRT, days	COD* Loading	VS* Loading	Function	Parameter	Feed	Multiple-Stage System Stage 1	Stage 2	Stage 3	Overall	Single-Stage System
MS: 9.071 **	0.515	0.240	Acetic Acid	Conc., mg/L	1304.10	1711.30	499.04	195.34	---	278.88
				Difference		-407.20	1212.26	303.70	---	1025.22
SS: 9.299	0.512	0.239		Reduction %		-23.79	70.83	60.85	85.02	78.61
			Propionic Acid	Conc., mg/L	949.48	1406.50	422.48	118.76	---	89.62
				Difference		-457.02	984.02	303.72	---	859.86
				Reduction %		-32.93	69.96	71.88	87.49	90.56
			Butyric Acid	Conc., mg/L	673.22	763.30	27.04	7.36	---	13.62
				Difference		-90.08	736.26	19.68	---	659.60
				Reduction %		-11.80	96.45	72.78	98.90	97.97
			Lipid	Conc., mg/L	9855.30	9645.30	5830.0	4352.0	---	5372.0
				Difference		210.00	3815.3	1478.0	---	4483.3
				Reduction %		2.13	39.55	25.35	55.84	45.49
			Protein	Conc., mg/L	22385.0	18602.0	15778.0	14163.0	---	17900.0
				Difference		3783.0	2824.0	1615.0	---	4485.0
				Reduction %		16.89	15.18	10.23	36.72	20.03
			Carbohydrate	Conc., mg/L	13985.0	11366.0	5830.0	4352.0	---	8076.9
				Difference		2619.0	5536.0	1478.0	---	5908.1
				Reduction %		18.72	48.70	25.35	68.88	42.24

* Loading: lb COD or VS / cuft-day.

** MS = Multiple-Stage, SS = Single-Stage.

Table 13: Digestion of Sludge Lipids, Proteins, and Carbohydrates and Production/Utilization of Organic Acids in Each Stage of the Multiple Stage System and the Single Stage System in Phase III-a.

Overall SRT, days	COD* Loading	VS* Loading	Function	Parameter	Feed	Multiple-Stage System Stage 1	Stage 2	Stage 3	Overall	Single-Stage System
MS:19.996 **	0.224	0.107	Acetic Acid	Conc., mg/L	1082.10	836.07	128.93	50.53	---	33.46
				Difference		246.03	707.14	78.40	---	1048.64
SS:20.525	0.220	0.106		Reduction %		22.73	84.57	60.81	95.33	96.90
			Propionic Acid	Conc., mg/L	933.00	1341.70	20.86	9.33	---	6.86
				Difference		-408.70	1320.84	11.53	---	926.14
				Reduction %		-30.46	98.44	55.27	99.00	99.26
			Butyric Acid	Conc., mg/L	471.93	423.33	1.20	0.00	---	2.67
				Difference		48.60	422.13	1.20	---	469.26
				Reduction %		10.29	99.71	100.00	100.00	99.43
			Lipid	Conc., mg/L	8150.9	6330.9	3449.9	2414.3	---	3175.3
				Difference		1820.0	2881.0	1035.6	---	4975.6
				Reduction %		22.32	45.50	30.02	70.37	61.04
			Protein	Conc., mg/L	26190.0	21853.0	20273.0	18900.0	---	20651.0
				Difference		4337.0	1580.0	1373.0	---	5539.0
				Reduction %		16.55	7.23	6.77	27.83	21.24
			Carbohydrate	Conc., mg/L	13328.0	8711.3	5633.3	3966.7	---	5757.8
				Difference		4616.7	3078.0	1666.6	---	2953.5
				Reduction %		34.63	35.33	29.58	70.23	33.90

* Loading: lb COD or VS / cuft-day.

** MS = Multiple-Stage, SS = Single-Stage.

Table 14: Digestion of Sludge Lipids, Proteins, and Carbohydrates and Production/Utilization of Organic Acids in Each Stage of the Multiple Stage System and the Single Stage System in Phase III-b.

Overall SRT, days	COD* Loading	VS* Loading	Function	Parameter	Feed	Multiple-Stage System Stage 1	Stage 2	Stage 3	Overall	Single-Stage System
MS:19.258 **	0.183	0.082	Acetic Acid	Conc., mg/L	555.71	499.00	80.71	6.43	---	34.85
				Difference		56.71	418.29	74.28	---	520.85
SS:19.264	0.176	0.079		Reduction %		10.20	83.25	92.03	98.84	93.72
			Propionic Acid	Conc., mg/L	353.00	583.93	6.57	1.29	---	0.50
				Difference		-230.93	577.36	5.28	---	352.50
				Reduction %		-39.54	98.87	80.42	99.63	99.85
			Butyric Acid	Conc., mg/L	188.43	168.21	1.29	0.0	---	0.28
				Difference		20.22	166.92	1.29	---	188.15
				Reduction %		10.73	99.23	100.00	100.00	99.85
			Lipid	Conc., mg/L	3990.00	2640.30	1510.0	1162.4	---	1762.3
				Difference		1349.70	1129.4	348.5	---	2227.7
				Reduction %		33.82	42.77	23.06	70.86	55.83
			Protein	Conc., mg/L	24957.0	21364.0	18979.0	17636.0	---	19136.0
				Difference		3593.0	2385.0	1343.0	---	5821.0
				Reduction %		14.39	11.16	7.07	29.33	23.32
			Carbohydrate	Conc., mg/L	6125.0	4837.5	2582.1	1730.4	---	4048.2
				Difference		1287.5	2255.4	851.7	---	2076.8
				Reduction %		21.02	46.62	32.98	71.74	33.90

* Loading: lb COD or VS / cuft-day.

** MS = Multiple-Stage, SS = Single-Stage.

Lipid, protein, and carbohydrate reductions in the multiple stage system were greater than in the single stage system. Volatile acids (acetate, propionate, and butyrate), lipid, and carbohydrate concentration profiles in the multiple stage system are shown in Figures 24, 25, 26, 27, and 28, respectively.

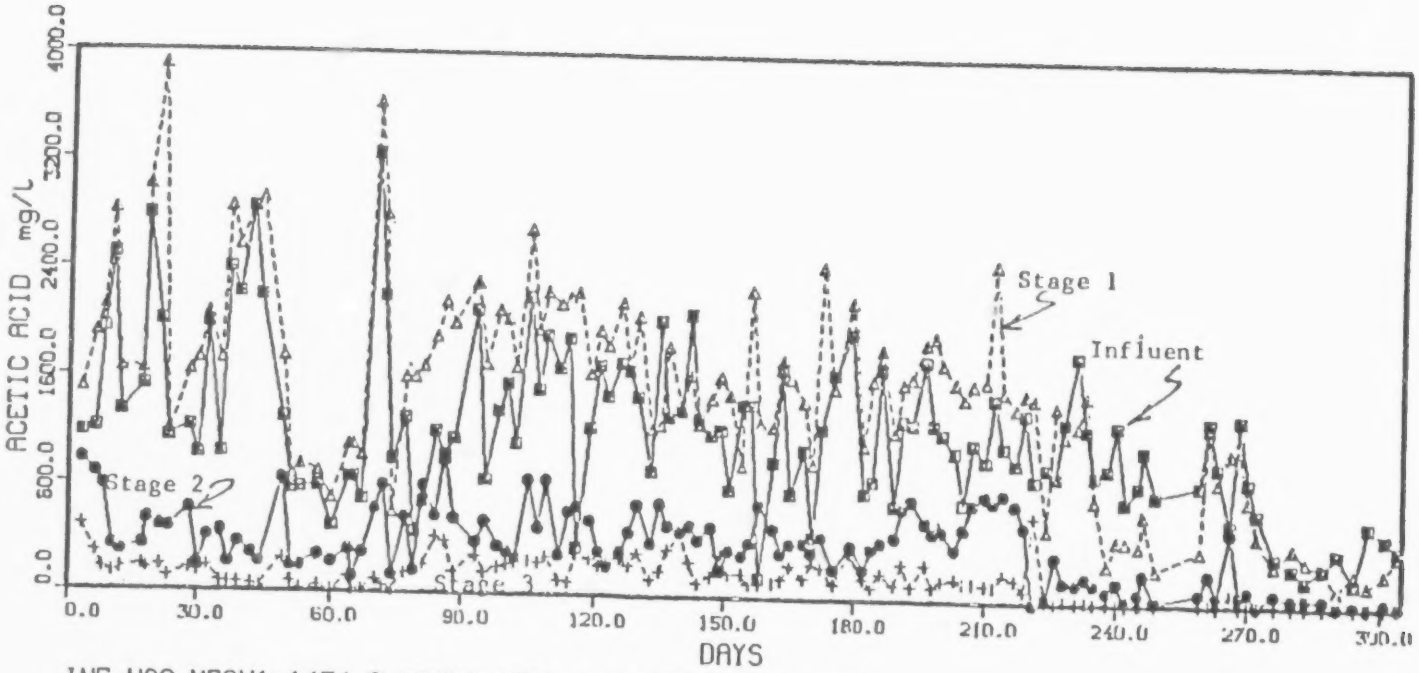
GAS PRODUCTION

The daily production of total gas, CH_4, and CO_2 is shown in Figures 29,30, and 31, respectively. The daily CH_4 and total gas generation per unit weight of VS added are shown in Figures 32 and 33, respectively. Figure 34 shows the daily total gas production per reactor unit volume, which takes into account the larger volume of the multiple stage system. The average CH_4 and CO_2 contents of the digesters as well as the yields and generation rates from the above figures are reported in Table 15, 16, 17, and 18.

As expected the methane yield and production rate were relatively small for the first stage digester, because of the short SRT, high VS loading, and low pH. As VS loading increased the methane yield and production rate appeared to decrease. Conversely, the methane yield and production rate in the first stage increased as the SRT increased. The increase in SRT also increased the total gas production and generation rate. It is also apparent that CO_2 production was greatest in the first stage digester. This is because the methane producing bacteria were not capable of optimum growth under the conditions in the digester.

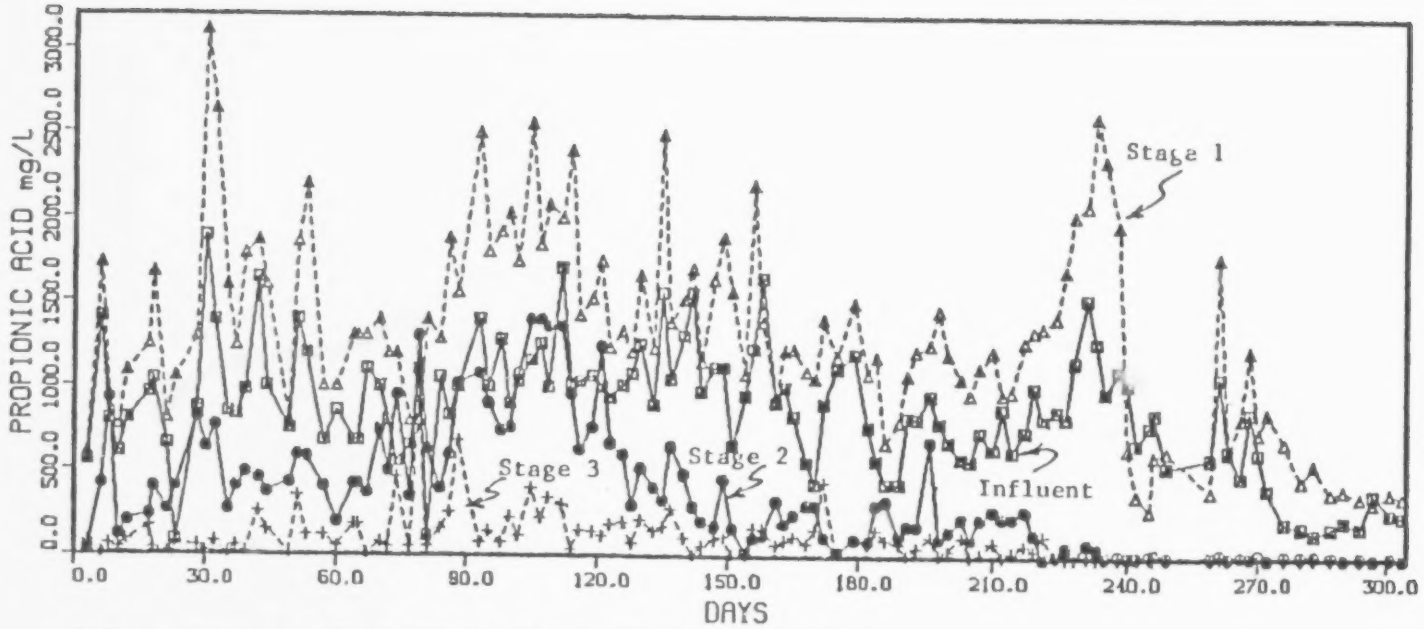
In all three Phases of the study it was observed that acid digestion in the first stage led to high production of total gas and methane in the second stage. As expected the second stage digester had the largest methane yield and generation rate of the three stages, because this digester was operated at a favorable pH condition for the methane producers. More importantly the second stage also out performed the single stage system in terms of methane yield and generation rate.

The second and third stage reactors produced smaller quantities of total gas and methane when the preceding digester(s) had longer SRTs and therefore had produced more total gas and methane themselves. As VS loading in the second stage increased, yields of total gas, CH_4, and CO_2 all increased, but the generation rates appeared to decrease. As



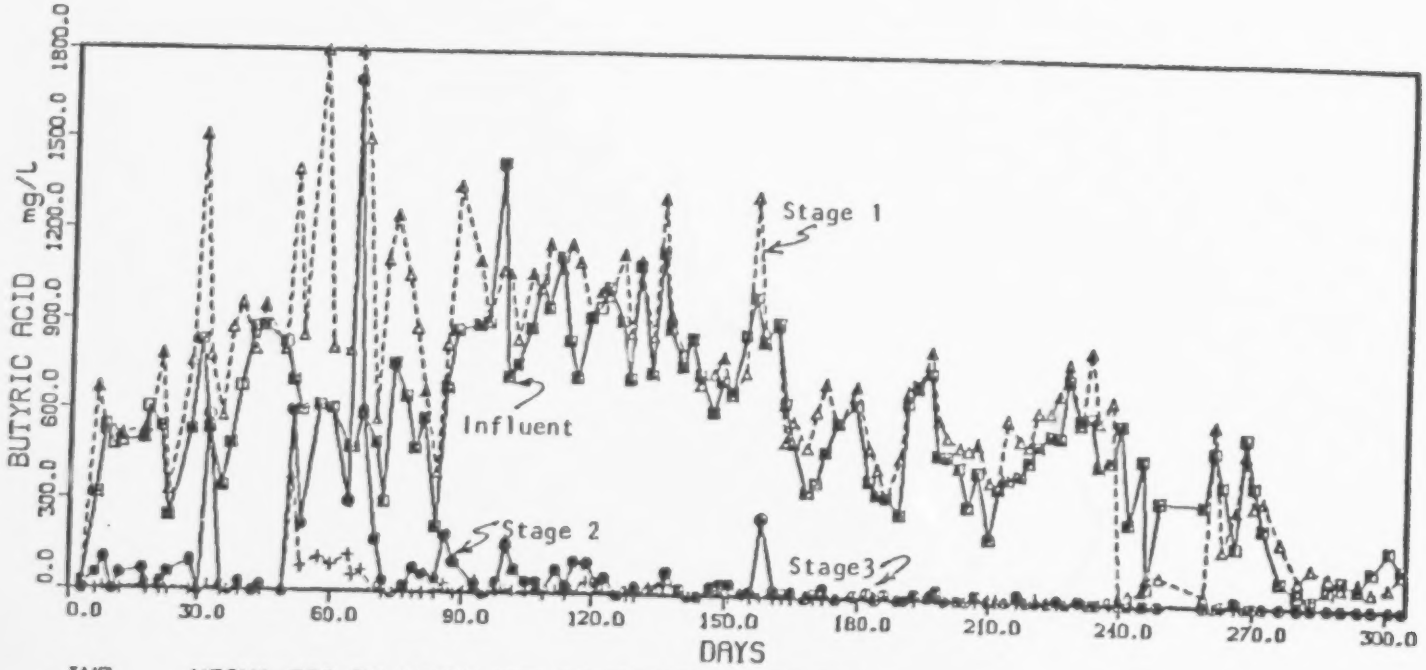
INF.HAC MEAN1-1454.2 MEAN2-1304.1 MEAN3-1082.1 PPM
STAGE 1 MEAN1-1910.6 MEAN2-1711.3 MEAN3- 830.1 PPM
STAGE 2 MEAN1- 454.6 MEAN2- 499.0 MEAN3- 128.9 PPM
STAGE 3 MEAN1- 151.9 MEAN2- 195.3 MEAN3- 50.5 PPM

Figure 24: Acetic Acid Concentration Profile in Each Stage of the Multiple-stage System at Phases I, II, and III



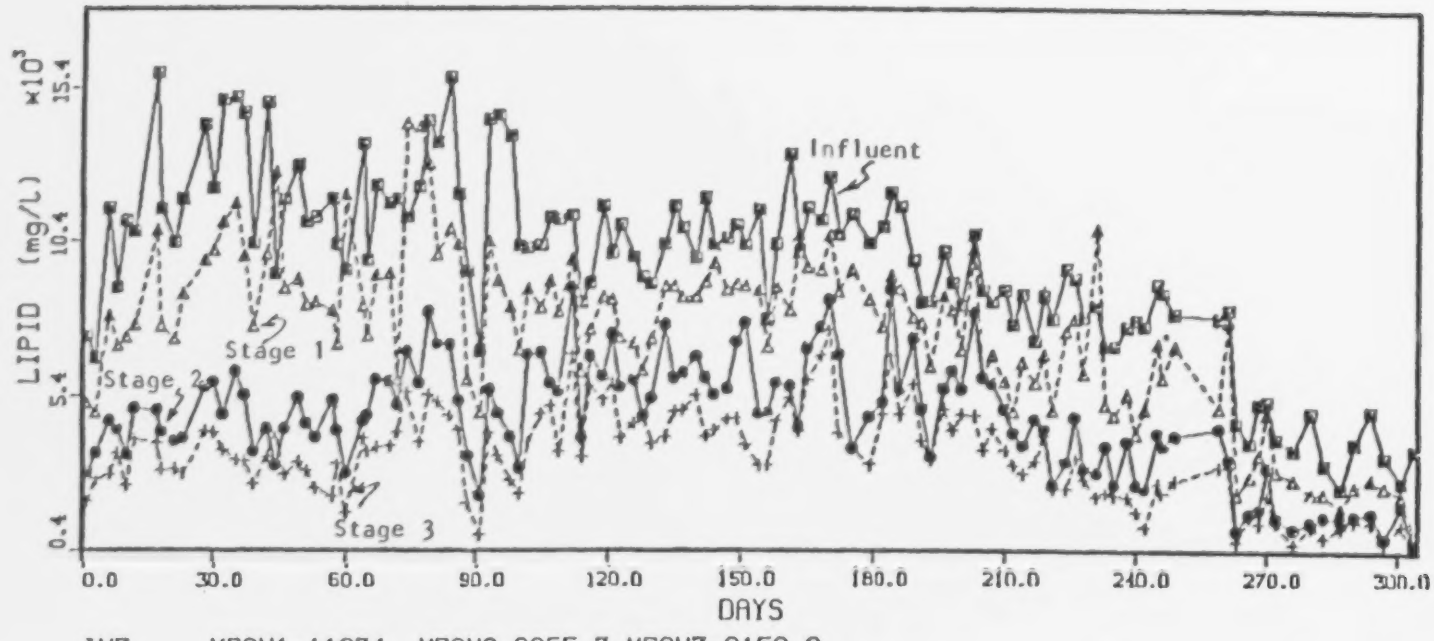
INF. MEAN1- 930.3 MEAN2- 949.5 MEAN3- 933.0 PPM
STAGE 1 MEAN1-1461.1 MEAN2-1406.5 MEAN3-1341.7 PPM
STAGE 2 MEAN1- 541.6 MEAN2- 422.5 MEAN3- 20.9 PPM
STAGE 3 MEAN1- 142.5 MEAN2- 118.8 MEAN3- 9.3 PPM

Figure 25: Propionic Acid Concentration Profile in Each Stage of the Multiple-stage System at Phases I, II, and III



INF. MEAN1-599.56 MEAN2-673.22 MEAN3-471.93 PPM
STAGE 1 MEAN1-885.04 MEAN2-763.30 MEAN3-423.33 PPM
STAGE 2 MEAN1-176.32 MEAN2- 27.04 MEAN3- 1.20 PPM
STAGE 3 MEAN1- 26.96 MEAN2- 7.36 MEAN3- 1.20 PPM

Figure 26: Butyric Acid Concentration Profile in Each Stage of the Multiple-stage System at Phases I, II, and III



INF. MEAN1-11834. MEAN2-9855.3 MEAN3-8150.9
STAGE 1 MEAN1-8985.1 MEAN2-9645.3 MEAN3-6330.9
STAGE 2 MEAN1-4783.7 MEAN2-5771.1 MEAN3-3449.7
STAGE 3 MEAN1-3267.6 MEAN2-4309.8 MEAN3-2414.3

Figure 27: Lipids Concentration Profile in Each Stage of the Multiple-stage System at Phases I, II, and III

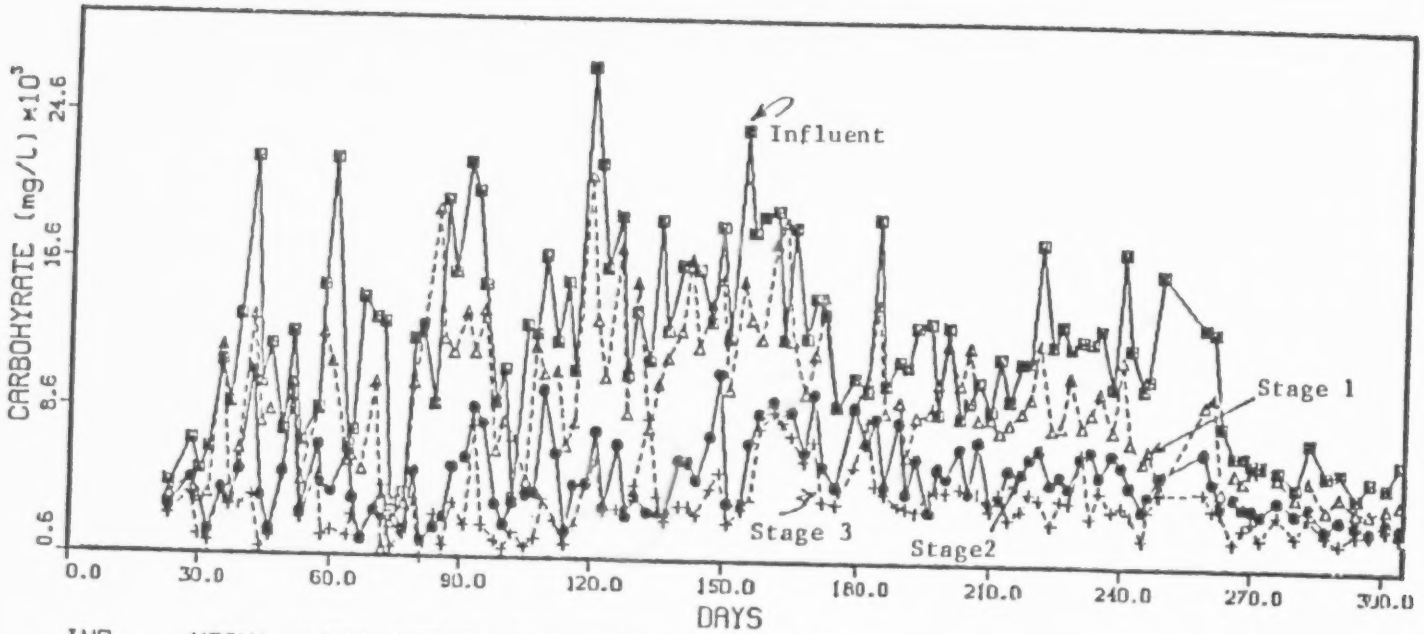


Figure 28: Carbohydrate Concentration profile in Each Stage of the Multiple-stage System at Phases I, II, and III

VS loading in the third stage increased, yields of all three gases increased, but the generation rates did no change significantly.

In terms of overall performance the total gas, CH_4, and CO_2 yields were significantly higher in the multiple stage system than in the single stage system. In fact the second stage alone produced significantly higher volume of gases than did the single stage system, even though it had a smaller volume and was operated at a shorter SRT. The single stage system and the overall multiple stage system showed similar trends with increasing VS loading; as loading increased all gas yields increased, but all generation rates appeared to decrease.

Anaerobic fermentation of organic substrate COD to methane is estimated on the basis of 1 mole of CH_4 equal to 64 grams of COD. The results of this theoretical conversion are shown in Table 19 with the observed data collected from both digestion systems.Table 19 shows that the COD-CH_4 mass conversion balanced fairly well for both digestion systems.

COLIFORM BACTERIA

The result of coliform analyses for the single and multiple stage systems are compared to data from the Hyperion Wastewater Treatment Plant (17) because the number of coliform bacteria in the feed sludge of the Hyperion plant was very similar to the feed sludge used for this study. The present study showed that the mean coliform bacteria level was reduced by 2.3 logs by the single stage system at the digestion temperature of 35.5°C. In the multiple stage system the mean coliform number decreased by 1.3 logs in the first stage, by 1.6 logs in the second stage, and by 2.0 logs in the third stage at digestion temperatures of 35.4°C, 35.5°, and 49.5°, respectively. The multiple stage reduction can be compared to the mean coliform reduction at the Hyperion two stage digestion system of 1.8 logs at 35.5°C and 3.1 logs at 49.4°C. The third stage thermophilic digester effluent contained no coliform bacteria when the multiple stage system was operated at the SRT and VS loading of 20 days and 0.085 lb VS/cu ft-day, respectively.

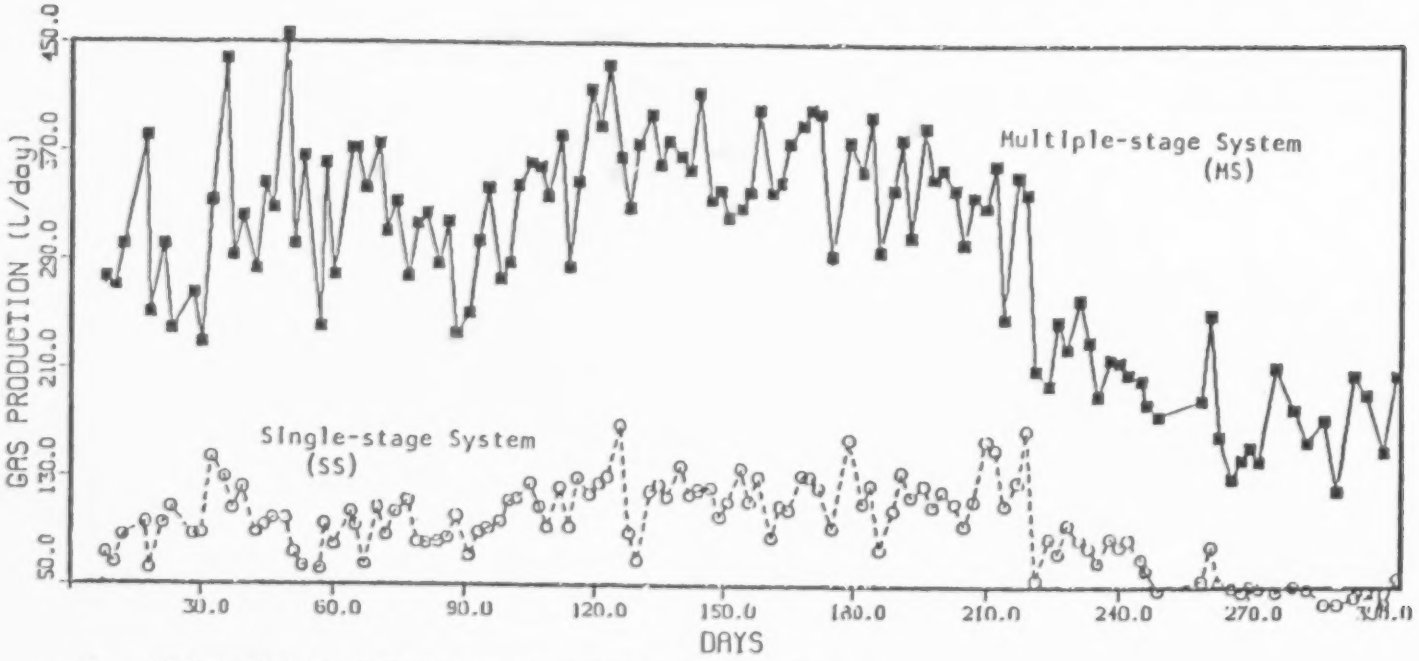


Figure 29: Daily Gas Production in the Single stage System and the Multiple Stage System

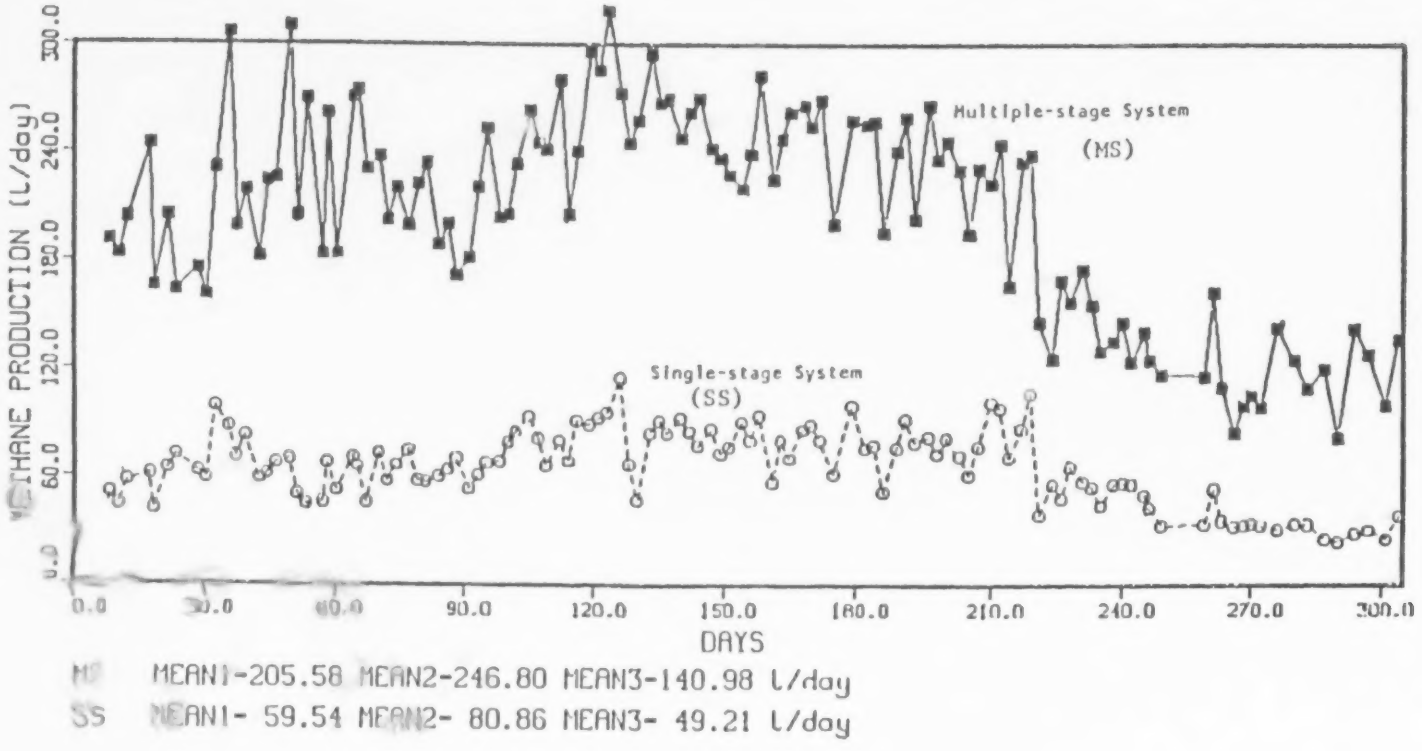


Figure 30: Daily Methane Production in the Single-stage System and the Multiple-stage System

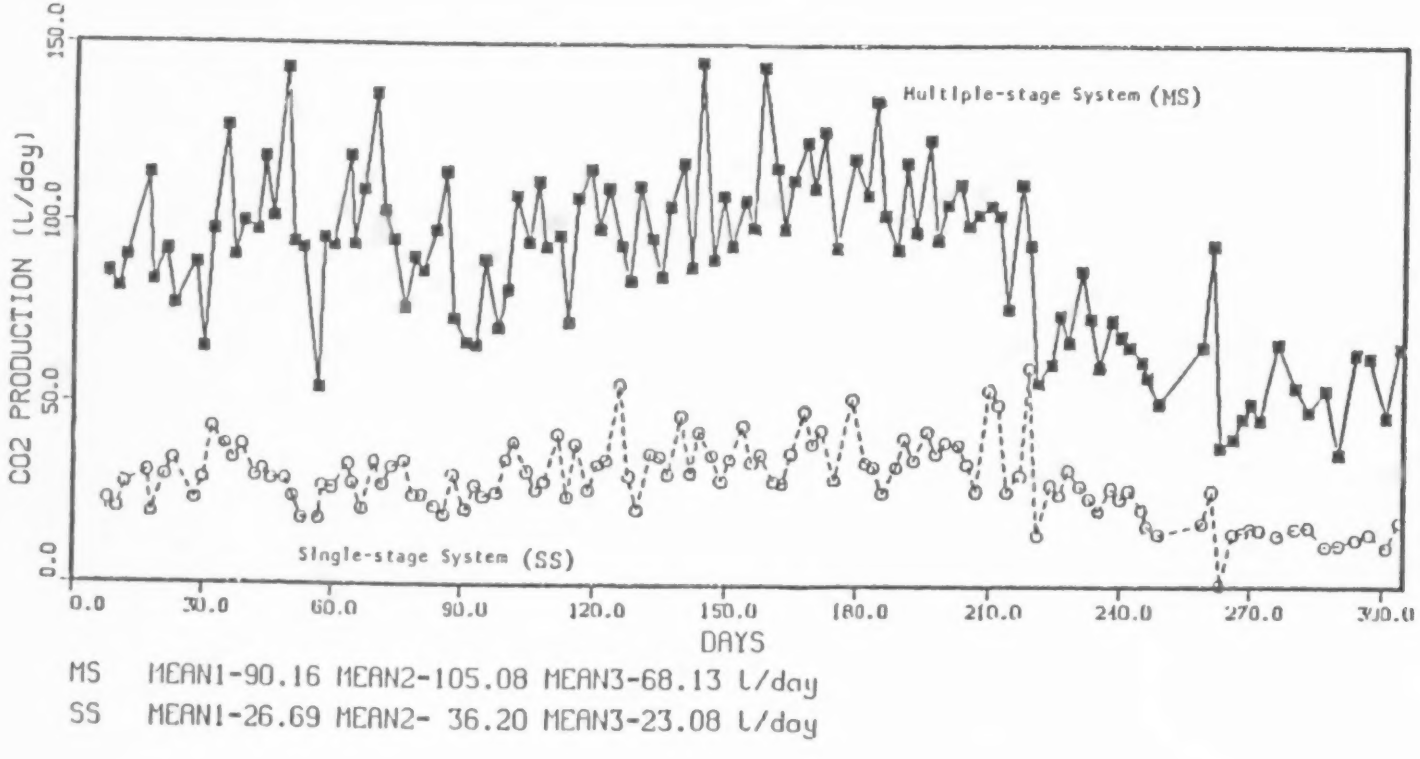
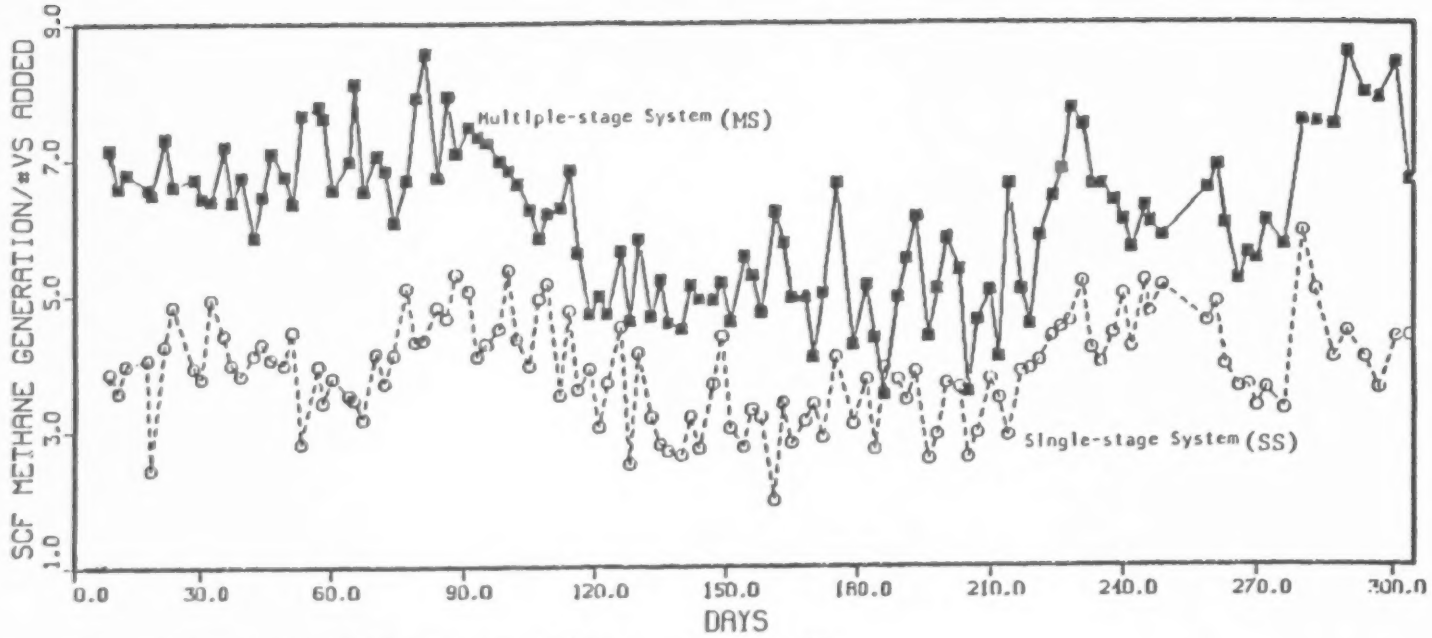


Figure 31: Daily CO_2 Production in the Single-stage System and the Multiple-stage System



MS MEAN1-6.721 MEAN2-5.181 MEAN3-6.491cu ft/lb

SS MEAN1-3.948 MEAN2-3.440 MEAN3-4.091cu ft/lb

Figure 32: Daily Methane Generation as SCF per Unit Weight of VS Added

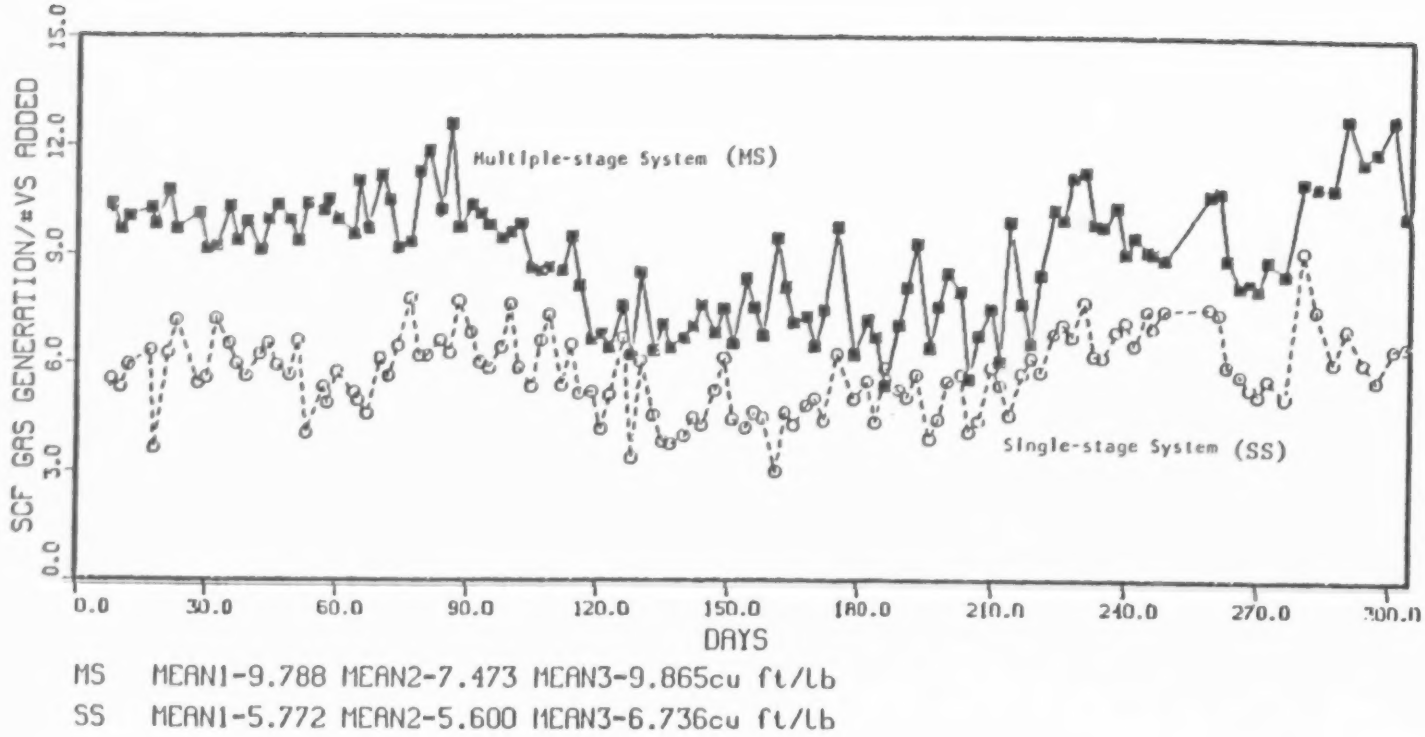


Figure 33: Daily Gas Generation as SCF per Unit Weight of VS Added

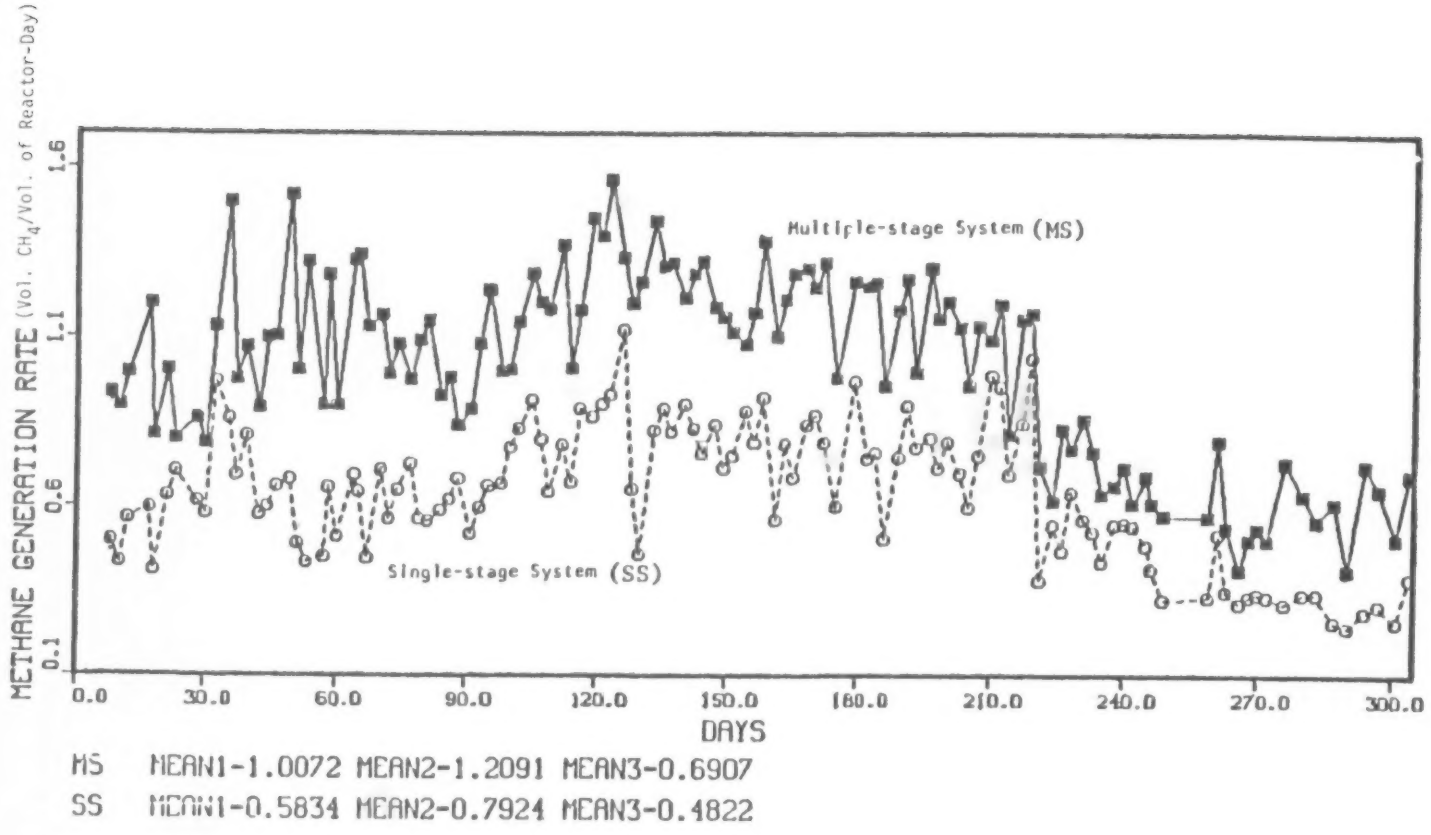


Figure 34: Daily Methane Generation Rate in the Single-stage System and the Multiple-stage System

Table 15: Total Gas, Methane, and CO_2 Production in Phase I

Phase I

Parameter	Multiple-Stage System				Single-Stage System
	Stage 1	Stage 2	Stage 3	Overall	
A. SRT, days	1.635	8.174	4.905	14.735	15.000
B. VS Loading, lb/cuft-day	1.035	0.135	0.221	0.149	0.148
C. pH	5.47	7.34	7.75		7.38
D. Gas Production					
1. Total Volume, l/day	28.51	231.16	39.13	298.80	86.96
2. Yield*					
SCF/#VS added	1.052	9.944	3.340	9.788	5.772
SCF/#VS destroyed	6.265	21.020	16.074	14.530	11.344
E. Methane Production					
1. Total Volume, l/day	8.915	159.99	36.675	205.58	59.54
2. % of Total Gas	31.27	69.21	68.01		65.22
3. Yield					
SCF/#VS added	0.329	6.929	2.260	6.721	3.948
SCF/#VS destroyed	1.959	14.471	10.120	10.049	7.820
4. Production Rate, l/day	0.267	1.547	0.424	1.007	0.583
F. CO_2 Production					
1. Volume, l/day	0.140	68.26	21.76	90.16	26.69
2. % of Total Gas	45.09	29.53	33.15		30.83

* SCF = Standard Cubic Foot

Table 16: Total Gas, Methane, and CO_2 Production in Phase II

Phase II

Parameter	Multiple-stage System				Single-stage System
	Stage 1	Stage 2	Stage 3	Overall	
A. SRT, days	1.008	5.039	3.024	9.071	9.299
B. VS Loading, lb/cuft-day	2.162	0.383	0.192	0.240	0.237
C. pH	5.60	7.54	7.84		7.62
D. Gas Production					
1. Total Volume, l/day	13.70	274.52	67.34	355.56	117.92
2. Yield*					
SCF/#VS added	0.299	6.546	3.073	7.473	5.600
SCF/#VS destroyed	2.626	14.073	20.365	12.326	11.404
E. Methane Production					
1. Total Volume, l/day	3.030	196.03	46.99	246.80	80.859
2. % of Total Gas	22.12	71.44	68.95		68.738
3. Yield					
SCF/#VS added	0.065	4.672	2.122	5.181	3.440
SCF/#VS destroyed	0.556	10.041	13.204	8.582	7.861
4. Production Rate, l/day	0.133	1.729	0.683	1.209	0.792
F. CO_2 Production					
1. Volume, l/day	7.698	77.465	19.921	105.08	36.197
2. % of Total Gas	56.34	28.23	29.66		30.61

* SCF = Standard Cubic Foot

Table 17: Total Gas, Methane, and CO_2 Production in Phase III-(a)

Phase III-(a)

Parameter	Multiple-stage System				Single-stage System
	Stage 1	Stage 2	Stage 3	Overall	
A. SRT, days	2.222	11.109	6.665	19.996	20.525
B. VS Loading, lb/cuft-day	0.962	0.145	0.157	0.107	0.106
C. pH	6.33	7.60	7.89		7.59
D. Gas Production					
1. Total Volume, l/day	36.239	145.41	31.917	213.57	73.794
2. Yield*					
SCF/#VS added	1.412	8.830	3.343	9.865	6.736
SCF/#VS destroyed	6.537	27.427	19.789	16.661	13.963
E. Methane Production					
1. Total Volume, l/day	17.162	103.02	20.797	140.98	49.207
2. % of Total Gas	46.10	70.93	64.77		66.70
3. Yield					
SCF/#VS added	0.808	6.275	2.021	6.491	4.598
SCF/#VS destroyed	3.251	18.246	12.513	10.977	9.309
4. Production Rate, l/day	0.757	0.909	0.306	0.691	0.482
F. CO_2 Production					
1. Volume, l/day	16.473	41.139	10.517	68.128	23.080
2. % of Total Gas	48.62	28.17	33.36		31.03

* SCF = Standard Cubic Foot

Table 18: Total Gas, Methane, and CO_2 Production in Phase-III(b)

Phase III-(b)

Parameter	Multiple-stage System				Single-stage System
	Stage 1	Stage 2	Stage 3	Overall	
A. SRT, days	1.489	11.118	6.651	19.258	19.264
B. VS Loading, lb/cuft-day	1.108	0.122	0.115	0.082	0.079
C. pH	6.34	7.56	7.87		7.61
D. Gas Production					
1. Total Volume, l/day	18.204	118.500	29.186	165.890	46.671
2. Yield*					
SCF/#VS added	1.124	8.790	4.123	10.175	6.176
SCF/#VS destroyed	6.537	21.469	20.427	18.192	13.204
E. Methane Production					
1. Total Volume, l/day	9.714	83.432	19.013	112.160	20.914
2. % of Total Gas	53.36	70.54	65.21		66.25
3. Yield					
SCF/#VS added	0.601	6.193	2.686	6.876	4.091
SCF/#VS destroyed	3.387	14.358	13.648	11.014	8.782
4. Production Rate, l/day	0.642	0.736	0.279	0.550	0.314
F. CO_2 Production					
1. Volume, l/day	7.187	34.679	9.792	51.558	13.355
2. % of Total Gas	38.66	29.14	33.01		28.82

* SCF = Standard Cubic Foot

Table 19: $COD-CH_4$ Mass Balance

	Phase I		Phase II	
	Single-Stage	Multiple-Stage	Single-Stage	Multiple-Stage
1. COD_{in}, grams/day	491.257	1001.619	499.267	1011.413
2. COD_{out}, grams/day	296.523	414.369	289.125	401.733
3. $COD_{removed}$, grams/day	194.734	587.250	210.142	609.680
4. $COD^*_{in\ methane}$, grams/day	179.371	602.828	197.457	618.514
5. Unbalanced Cod (3) - (4)	15.363	-15.578	12.685	-8.834
6. % Error $\frac{(3) - (4)}{(4)}$	8.6	-2.6	6.4	-1.4

	Phase III-(a)		Phase III-(b)	
	Single-Stage	Multiple-Stage	Single-Stage	Multiple-Stage
1. COD_{in}, grams/day	357.282	731.051	271.702	594.641
2. COD_{out}, grams/day	201.441	337.021	174.518	239.012
3. $COD_{removed}$, grams/day	155.841	394.030	97.194	355.629
4. $COD^*_{in\ methane}$, grams/day	140.591	402.800	88.325	320.457
5. Unbalanced COD (3) - (4)	15.25	-8.770	8.859	35.172
6. % Error $\frac{(3) - (4)}{(4)}$	1.1	-2.2	10	11

* Theoretical Conversion (1 mole CH_4 = 64 grams of COD)

Table 20: Comparison of Coliform Bacteria Numbers Obtained from Hyperion Wastewater Treatment Plant and This Study

Parameters	Raw Sludge Range From	Raw Sludge Range To	Raw Sludge Mean	Mesophilic Sludge Range From	Mesophilic Sludge Range To	Mesophilic Sludge Mean	Thermophilic Sludge Range From	Thermophilic Sludge Range To	Thermophilic Sludge Mean
Hyperion WTP									
Temperature ^{o}C	23.0	28.9	26.7	34.5	35.6	35.6	47.8	51.1	49.4
Coliform Bacteria #/100 ml	1.25×10^{7}	3.1×10^{9}	4.5×10^{8}	1.8×10^{6}	3.3×10^{7}	7.8×10^{6}	1.0×10^{2}	9.2×10^{4}	5.4×10^{3}
This Study									
Feed									
Temperature ^{o}C	21.0	27.0	23.8						
Coliform Bacteria #/100 ml	1.3×10^{7}	1.2×10^{8}	5.3×10^{7}						
* Multiple-Stage System									
a. 1st Stage									
Temperature ^{o}C				35.0	37.5	35.4			
Coliform Bacteria				5.3×10^{5}	1.0×10^{7}	2.4×10^{6}			
b. 2nd Stage									
Temperature ^{o}C				34.0	37.0	35.5			
Coliform Bacteria				1.2×10^{4}	1.2×10^{6}	6.4×10^{4}			
c. 3rd Stage									
Temperature ^{o}C							45.0	50.0	49.5
Coliform Bacteria							0	1.2×10^{3}	7.1×10^{2}
* Single-Stage System									
Temperature ^{o}C				-	-	35.5			
Coliform Bacteria				7.4×10^{4}	1.0×10^{6}	2.5×10^{5}			

* Average of 20 data collected at SRT = 9, 15 and 20 days
VS Loading = 0.240, 0.149 and 0.082 #/ft^{3}-day

FILTERING AND DEWATERING PROPERTIES OF DIGESTED SLUDGE

Nine tests were conducted on digester effluent from both the single stage system and the multiple stage system to determine the effect of chemical conditioners on the sludge filtering and dewatering characteristics. The results of these tests are shown in Table 21. It is apparent from Table 21 that the specific resistance of the multiple stage digested sludge is lower than that of the single stage digested sludge when both systems are operated at the same condition. A typical curve which illustrates the influence of conditioner addition on the sludges is Figure 35. It shows that the sludge filterability, as measured by specific resistance, improved as a result of using a sludge conditioner. However, the addition of sludge conditioner in excess of the optimum caused re-stabilization of the sludge flocs/particles and an increase in specific resistance.

Table 21 shows that a high molecular organic polymer (American Cyanamid -1563C) was more effective than a low molecular one (American Cyanamid-581C). The multiple stage digested sludge had a lower conditioner dosage requirement than the single stage digested sludge, but this might be attributed to the higher initial specific resistance of the single stage digested sludge. The SVI of the multiple stage digested sludge was slightly lower than that of the single stage digested sludge, according to Table 21. However, for both digestion systems, the sludges with proper chemical treatment settled and compacted well within 30 minutes.

METAL ACCUMULATION

The concentrations of metals (Cd, Cu, Mn, Ni, Pb, and Zn) found in the influent feed sludge and in the digested sludge from the single stage and the multiple stage systems are reported in Tables 22, 23, and 24. No metal was found in the filtrate samples; all metals were associated with the digested sludge solids.

PERFORMANCE OF WET AIR OXIDATION (WAO)

Thermal treatment by WAO was studied for further destruction of digester effluent residuals. The purpose of this portion of the study was four fold: first, to establish the effectiveness of wet air oxidation on the destruction of anaerobic sludge solids; second, to

Table 21: Filterability and Settleability of Digested Sludges

Phase	Mean * SRT	Mean * VS Loading #/ft^3-day	Chemical Used**	Optimum Dosage mg/l SS	Optimum Dosage mg/l MS	Specific Resistance, m/Kg x 10^{12} Single Stage Initial	Single Stage Lowest	Single Stage Reduction	Multiple-Stage Initial	Multiple-Stage Lowest	Multiple-Stage Reduction	SVI, ml/g Single-Stage	SVI, ml/g Multiple Stage
I	8.25/ 8.65	0.239/0.228	AC-1563C	800	600	50.71	3.08	47.63	33.45	3.05	30.40	-	-
			AC-1563C	1200	900	43.65	1.04	42.61	37.57	0.88	36.69	33	32
			AC-1563C	1000	800	55.62	2.01	53.61	36.00	2.01	33.99	24	21
			AC-1563C	900	630	37.08	0.58	36.50	29.33	0.48	28.85	-	-
II	15.64-17.00	0.111/0.103	AC-1563C	800	700	29.43	0.31	29.12	25.99	0.64	25.35	21.5	20.0
			AC-1563C	800	600	26.38	0.46	25.92	21.09	0.29	20.80	36.2	28.2
			AC- 581C	5000	2000	27.46	1.58	25.88	22.26	0.92	21.34	-	-
III	19.72/22.04	0.093/0.122	AC-1563C	700	450	24.62	1.35	23.27	16.57	0.77	15.80	32	20
			AC-1563C	600	400	23.54	0.82	22.72	18.83	0.51	18.32	31.4	26.9

MS = Multiple-Stage, SS = Single-Stage

* MS/SS
** AC = America Cyanamid

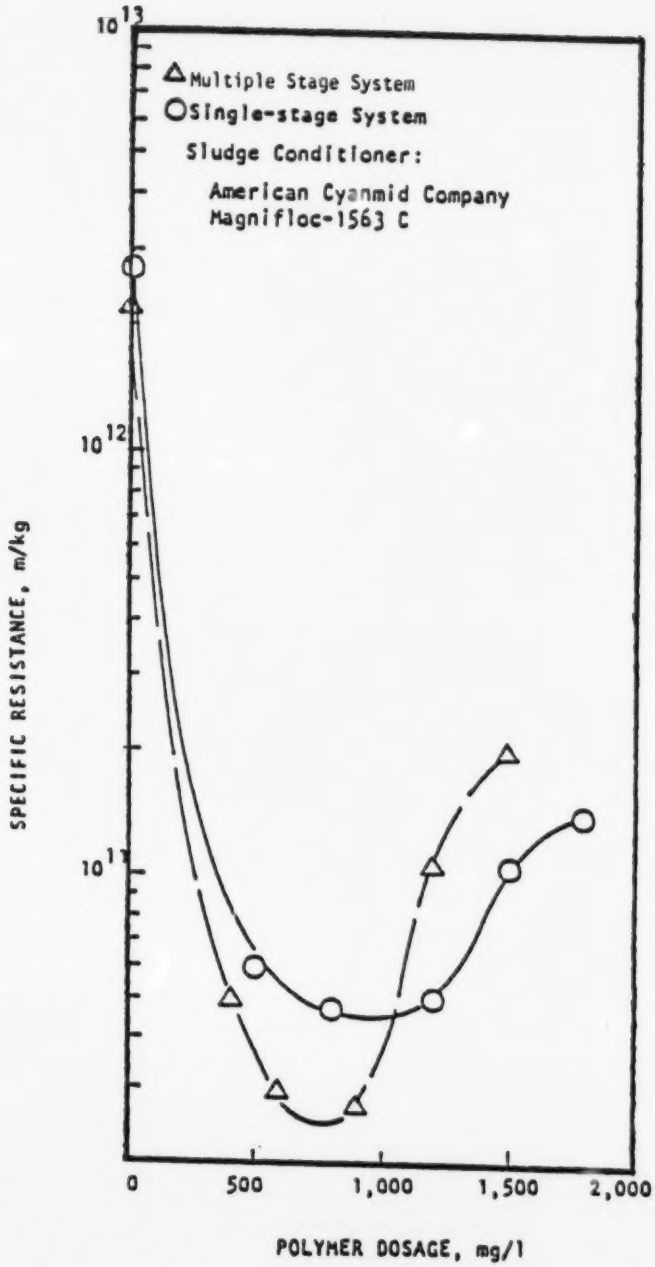


Figure 35: Specific Resistance as a Function of Conditioner Dosage

Table 22: Metals Concentration in WAO Influent Sludge

Date	Concentration, mg/kg					
	Cd	Cu	Mn	Ni	Pb	Zn
1- 3	26.94	331.31			335.30	
1-13	30.44	328.44			283.22	
1-27	45.62	256.36			143.05	
2- 3	21.41	258.68			221.98	
2-13	7.25	212.33			206.00	
2-17	30.31	214.14			124.79	
2-24	23.54	238.96			96.91	
3- 2	22.02	242.02			311.84	
3- 9	17.59	247.50			207.74	
3-16	35.11	226.89			436.96	
3-30	33.00	288.46			452.36	
4- 9	32.84	236.99			364.85	
4-13	32.50	265.44			424.30	
4-20	24.76	212.55			257.42	
5- 5	26.37	226.39			328.22	
5-21	20.53	434.86	281.79	83.49	160.72	1321.97
5-25	18.17	415.68	354.10	43.11	240.17	1077.69
6- 4	10.71	369.21	424.59	36.92	206.76	959.94
6- 9	14.42	436.07	368.98	80.50	187.84	1039.85
6-11	18.08	368.08	384.51	64.09	345.08	969.50
6-18	18.44	392.21	405.62	72.07	395.56	1005.67
6-25	21.68	420.43	361.31	70.62	420.43	1018.23
7- 6	20.84	440.02	357.31	64.51	403.63	1157.94
7-18	22.32	593.04	403.13	71.63	329.84	1332.67
7-25	21.88	570.16	331.49	71.27	202.21	1160.21
8- 3	27.41	807.42	348.88	69.78	304.03	1594.90
8- 8	34.45	898.79	319.57	92.38	424.43	1997.30
8-15	18.38	643.13	372.34	50.77	478.72	1426.50
8-22	24.74	856.10	381.03	69.28	519.60	1781.47
8-29	72.24	817.06	383.62	92.17	448.39	1494.62
9- 5	71.75	831.31	390.91	74.22	544.31	1731.90
9-10	57.09	893.66	307.81	78.44	198.59	1489.43
9-17	55.26	865.01	297.95	75.93	288.34	1393.63
9-24	40.00	815.00	260.00	132.50	200.00	1650.00
10- 3	42.37	787.68	209.38	78.77	149.56	2019.04
10-10	39.89	658.12	234.33	109.69	149.57	1645.31
10-19	31.11	518.57	375.35	88.90	197.55	1234.69
10-26	15.95	468.41	318.92	50.32	249.15	1420.17
11- 2	28.89	473.20	318.79	50.31	298.86	1319.98
11- 9	0.00	586.12	379.11	50.38	249.41	2194.84
11-16	36.98	549.75	344.84	78.96	199.91	3123.59
11-23	39.93	474.12	344.36	78.85	299.45	2146.03
11-30	39.97	534.57	319.74	78.94	299.76	2248.20
12- 7	0.00	400.00	280.00	53.33	266.67	1566.67
12-14	0.00	449.51	415.97	53.67	268.37	1777.93

Table 23: Metals Concentration in the WAO Effluent of the Multiple Stage Digestion System

Date	Cd		Cu		Mn		Ni		Pb		Zn	
	Slg	Fil	Slg	Fil	Slg	Fil	Slg	Fil	Slg	Fil	Slg	Fil
1- 3	53.89	0.00	129.07	0.00	2147.35	0.00	75.90	0.00	152.44	0.00		
1-13	68.29	0.00	1554.38	0.00	2507.75	0.00	133.11	0.00	138.54	0.00		
1-27	84.89	0.00	1604.76	0.00	2585.02	0.00	153.25	0.00	132.89	0.00		
2- 3	86.74	0.00	1628.14	0.00	2624.39	0.00	130.46	0.00	156.62	0.00		
2-13	94.41	0.00	1488.97	0.00	1747.58	0.00	51.37	0.00	102.05	0.00		
2-24	107.82	0.00	1411.51	0.00	2910.15	0.00	170.16	0.00	486.57	0.00		
3- 5	92.32	0.00	1598.31	0.00	2827.43	0.00	772.04	0.00	472.74	3.40		
3-16	91.10	0.00	1350.32	0.00	2030.66	0.00	193.03	0.00	376.17	0.00		
4- 9	74.92	0.00	1219.59	0.00	1594.33	0.00	222.94	0.00	772.43	0.00		
4-13	82.25	0.00	1562.06	0.00	2321.65	0.00	200.54	0.00	573.43	0.00		
5- 6	13.14	0.00	383.23	0.00	591.26	0.00	109.49	0.00	339.43	0.00	1040.18	0.00
5-14	33.76	0.00	601.39	0.00	601.39	0.00	105.51	0.00	443.13	3.73	1878.03	0.00
5-21	25.27	0.00	586.33	0.00	545.90	0.00	101.92	0.00	424.59	0.00	1839.87	0.00
5-25	40.60	0.00	698.71	0.00	457.94	0.00	113.30	1.08	396.56	0.00	2643.75	0.00
6- 4	22.37	0.00	490.04	0.00	516.67	0.00	93.75	0.00	383.51	0.00	1438.16	0.00
6- 9	36.87	0.00	647.73	0.00	597.91	0.00	69.76	0.00	418.54	0.00	1893.37	0.00
6-11	35.61	0.00	604.47	0.00	604.47	0.00	120.89	1.42	856.34	0.00	1914.16	0.00
6-18	38.86	0.00	639.69	0.00	625.47	0.00	132.68	0.00	445.41	0.00	1800.61	0.00
6-25	35.18	0.00	572.98	0.00	603.14	0.00	130.68	0.00	572.98	0.00	1608.36	0.00
7- 6	38.68	0.00	679.25	0.00	622.64	0.00	141.51	0.00	349.06	0.00	1933.96	0.00
7-18	42.86	0.00	802.41	0.00	702.11	0.00	118.54	0.00	638.28	0.00	2006.02	0.00
7-25	39.19	0.00	746.55	0.00	765.21	0.00	111.98	0.00	653.23	0.00	1913.03	0.00
8- 3	35.91	0.00	798.08	0.00	738.23	0.00	139.66	0.00	847.96	0.00	1815.64	0.00
8- 8	40.95	0.00	1098.79	0.00	679.25	0.00	139.85	0.00	749.18	0.00	2147.64	0.00
8-15	36.84	0.00	1168.70	0.00	227.07	0.00	152.44	0.00	952.74	0.00	2350.10	0.00
8-22	33.95	0.00	1125.34	0.00	485.06	0.00	126.12	0.00	358.94	0.00	2134.26	0.00
8-29	37.45	0.00	1169.06	0.00	456.66	0.00	168.97	0.00	639.33	0.00	2374.65	0.00
9- 5	58.74	0.00	1305.36	0.00	438.23	0.00	139.86	0.00	344.99	0.00	2750.58	0.00
9-10	57.86	0.00	947.73	0.00	518.75	0.00	79.81	0.00	99.76	0.00	1695.93	0.00
9-17	57.09	0.00	935.04	0.00	580.71	0.00	99.41	0.00	98.43	0.00	1673.22	0.00
9-24	105.00	0.00	1100.00	0.00	520.00	0.00	80.00	0.00	200.00	0.00	2000.00	0.00
10- 3	79.73	0.00	1275.66	0.00	518.24	0.00	100.66	0.00	398.64	0.00	2491.53	0.00
10-10	79.86	0.00	1227.79	0.00	539.03	0.00	100.82	0.00	598.92	0.00	2844.88	0.00
10-19	57.04	0.00	963.71	0.00	462.19	0.00	78.67	0.00	393.35	0.00	2310.95	0.00
10-26	62.77	0.00	976.39	0.00	418.45	0.00	102.62	0.00	199.26	0.00	2690.05	0.00
11- 2	44.94	0.00	699.02	0.00	299.58	0.00	100.86	0.00	199.72	0.00	1747.55	0.00
11- 9	31.72	0.00	456.03	0.00	396.55	0.00	53.53	0.00	198.28	0.00	1387.93	0.00
11-16	62.07	0.00	817.73	0.00	463.05	0.00	155.67	0.00	394.09	0.00	2807.88	0.00
11-23	52.20	0.00	695.97	0.00	545.18	0.00	62.64	0.00	347.99	0.00	3073.89	0.00
11-30	0.00	0.00	535.90	0.00	696.68	0.00	0.00	0.00	535.91	0.00	1808.68	0.00
12- 7	36.49	0.00	775.27	0.00	485.71	0.00	0.00	0.00	280.22	0.00	3362.60	0.00
12-14	0.00	0.00	747.47	0.00	525.25	0.00	80.80	0.00	404.04	0.00	3030.30	0.00

Note: Slg = Sludge, Fil = Filtrate.

Units: Sludge, mg/kg; Filtrate, mg/L.

Table 24: Metals Concentration in the WAO Effluent of the Single Stage Digestion System

Date	Cd		Cu		Mn		Ni		Pb		Zn	
	Slg	Fil	Slg	Fil	Slg	Fil	Slg	Fil	Slg	Fil	Slg	Fil
1- 3	63.19	0.00	1493.05	0.00	2894.98	0.00	153.66	0.00	159.94	5.42		
1-13	64.73	0.00	1482.97	0.00	1728.85	0.00	104.64	0.00	136.34	5.42		
1-27	80.52	0.00	1503.89	0.00	2363.38	0.00	52.61	0.00	104.67	8.57		
2- 3	76.54	0.00	1455.26	0.00	2856.49	0.00	227.76	0.00	477.60	0.00		
2-13	85.49	0.00	1260.73	0.00	2718.68	0.00	126.58	0.00	408.17	3.75		
2-17	103.75	0.00	1574.54	0.00	3177.69	0.00	123.57	0.00	398.48	3.65		
2-24	94.44	0.00	1384.86	0.00	2785.58	0.00	97.04	0.00	557.61	0.00		
3- 5	101.09	0.00	1560.94	0.00	1933.31	0.00	227.72	0.00	477.51	0.00		
3- 9	86.37	0.00	1257.83	0.00	2121.86	0.00	183.28	0.00	393.06	0.00		
3-16	99.06	0.00	1325.66	0.00	2599.34	0.00	222.73	0.00	350.29	0.00		
3-30	82.75	0.00	1346.96	0.00	2579.30	0.00	120.09	0.00	516.32	0.00		
4- 9	89.56	0.00	1573.53	0.00	1599.52	0.00	180.09	0.00	772.43	0.00		
4-13	74.92	0.00	1355.97	0.00	2104.42	0.00	120.89	0.00	675.31	0.00		
5- 6	26.51	0.00	641.74	0.00	565.01	0.00	69.75	0.00	390.63	0.00	2162.39	0.00
5-14	18.85	0.00	659.69	0.00	596.86	0.00	73.30	0.00	376.96	0.00	2146.60	0.00
5-21	33.20	0.00	673.43	0.00	569.10	0.00	113.82	0.00	341.46	0.00	2371.24	0.00
5-25	29.41	0.00	707.98	0.00	609.96	0.00	76.24	1.08	337.65	0.00	2178.41	0.00
6- 4	27.74	0.00	687.41	0.00	602.99	0.00	84.42	0.00	373.85	0.00	1929.57	0.00
6- 9	26.39	0.00	686.09	0.00	654.42	0.00	73.89	0.00	327.21	0.00	1741.61	0.00
6-11	30.96	0.00	649.22	0.00	639.23	0.00	69.92	0.00	519.38	0.00	1817.82	0.00
6-18	30.13	0.00	583.09	0.00	621.96	0.00	68.03	0.00	641.40	0.00	1729.83	0.00
6-25	25.32	0.00	584.40	0.00	681.80	0.00	116.88	0.00	594.14	0.00	1538.91	0.00
7- 6	30.90	0.00	741.66	0.00	724.00	0.00	83.88	0.00	538.58	0.00	1854.14	0.00
7-18	34.99	0.00	124.96	0.00	599.82	0.00	129.96	0.00	699.79	0.00	2099.37	0.00
7-25	35.61	0.00	793.49	0.00	712.11	0.00	122.08	0.00	671.41	0.00	1932.86	0.00
8- 3	30.69	0.00	871.29	0.00	653.47	0.00	82.18	0.00	742.57	0.00	1658.42	0.00
8- 8	25.65	0.00	926.54	0.00	529.45	0.00	99.27	0.00	306.09	0.00	1985.44	0.00
8-15	21.89	0.00	706.02	0.00	567.16	0.00	119.40	0.00	308.46	0.00	1810.95	0.00
8-22	29.26	0.00	975.32	0.00	555.93	0.00	146.30	0.00	302.35	0.00	2145.71	0.00
8-29	41.68	0.00	1022.13	0.00	635.11	0.00	119.08	0.00	605.33	0.00	2083.95	0.00
9- 5	46.83	0.00	916.61	0.00	657.57	0.00	119.56	0.00	607.75	0.00	1813.29	0.00
9-10	57.65	0.00	1093.44	0.00	536.78	0.00	53.68	0.00	596.42	0.00	2137.18	0.00
9-17	78.67	0.00	1052.22	0.00	580.19	0.00	99.32	0.00	491.69	0.00	2261.78	0.00
9-24	84.75	0.00	1171.49	0.00	518.44	0.00	100.70	0.00	498.50	0.00	2293.12	0.00
10- 3	73.64	0.00	1132.28	0.00	386.63	0.00	92.98	0.00	368.22	0.00	2301.39	0.00
10-10	57.54	0.00	1140.87	0.00	466.27	0.00	102.18	0.00	198.41	0.00	2628.97	0.00
10-19	62.22	0.00	1086.31	0.00	464.15	0.00	99.74	0.00	395.02	0.00	2765.16	0.00
10-26	62.41	0.00	851.91	0.00	346.71	0.00	79.25	0.00	396.24	0.00	2476.47	0.00
11- 2	57.33	0.00	632.66	0.00	514.04	0.00	53.38	0.00	395.41	0.00	2075.92	0.00
11- 9	0.00	0.00	127.08	0.00	459.43	0.00	98.73	0.00	293.26	0.00	2590.42	0.00
11-16	0.00	0.00	529.21	0.00	305.31	0.00	104.82	0.00	305.31	0.00	2086.30	0.00
11-23	62.04	0.00	738.63	0.00	610.60	0.00	99.47	0.00	295.45	0.00	2954.50	0.00
11-30	0.00	0.00	648.57	0.00	422.32	0.00	0.00	0.00	301.66	0.00	2714.93	0.00
12- 7	57.41	0.00	732.53	0.00	346.47	0.00	99.98	0.00	197.98	0.00	3118.19	0.00
12-14	0.00	0.00	623.01	0.00	348.88	0.00	179.43	0.00	299.04	0.00	2342.50	0.00

Note: Slg = Sludge, Fil = Filtrate.

Units: Sludge, mg/kg; Filtrate, mg/L.

understand the influences of temperature and solids concentration on WAO performance; third, to investigate the destruction efficiency of WAO on filtration sludge cake; and fourth, to investigate the stabilization of metals by WAO.

The effect of temperature on the destruction of volatile solids in the effluent sludge from the multiple stage system at SRTs of 9 and 15 days and in the effluent sludge from the single stage system at an SRT of 9 days is shown in Figure 36. It is apparent from this figure that the efficiency of volatile solids destruction was a function of temperature. When the temperature was below 180°C, the fraction of volatile solids which was oxidized increased relatively little. The percent of volatile solids destroyed increased sharply between 180°C and 250°C. Thereafter, it remained fairly constant, even when the temperature was raised as high as 300°C. Figure 36 also shows that the influence of temperature was similar for the single stage digested sludge and for the multiple stage digested sludge at both 9 and 15 day SRTs.

Also shown in Figure 36 is data for the Levittown sludge (39). The Levittown sludge showed a similar temperature effect, but it was more readily oxidized. The fraction of volatile solid destroyed at 250°C was 96% for the Levittown sludge compared to 86% for Alcosan sludge. (The residual was assumed to be a non-oxidizable volatile fraction). This result was expected because the Levittown study dealt only with biological activated sludge whereas this study investigated digested primary and secondary sludges.

The effects of percent influent volatile solids and temperature on the percent volatile solids remaining in the WAO effluent is illustrated in Figure 37, which shows that the higher the percent WAO influent volatile solids or the lower the temperature, the higher the percent WAO effluent volatile solids. However, at temperatures of 250°C and 275°C, there was no significant difference between influent and WAO effluent volatile solids concentrations. The data in Figures 37 and 38 also showed a linear relationship between the influent and the WAO effluent in terms of both volatile and non-volatile solids.

This linear relationship indicates that the percent reductions were constant at about 86% at 250°C and 275°C, and independent of the influent concentrations. Figure 39 shows that unlike the volatile and non-volatile solids data in Figures 37 and 38, the COD data is not linear.

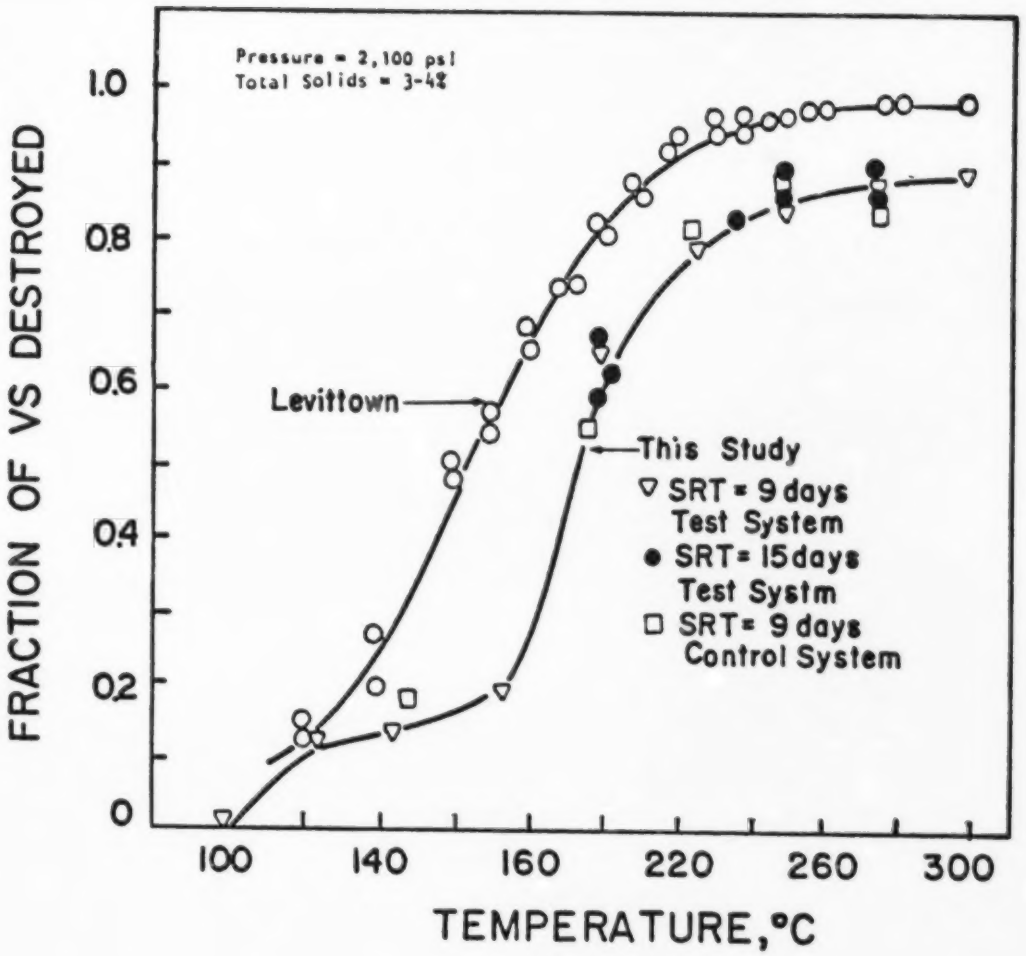


Figure 36: Volatile Solids Destruction as a Function of Temperature

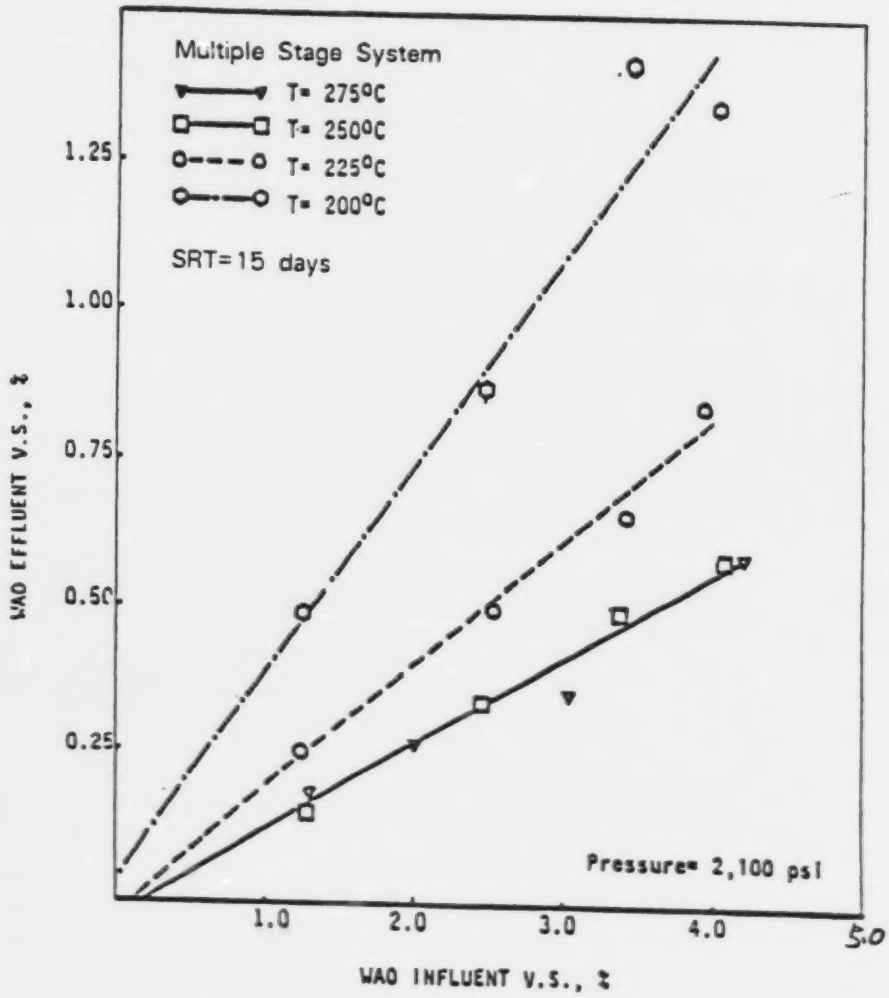


Figure 37: Percent Volatile Solids in WAO Influent and Effluent at Different Temperatures

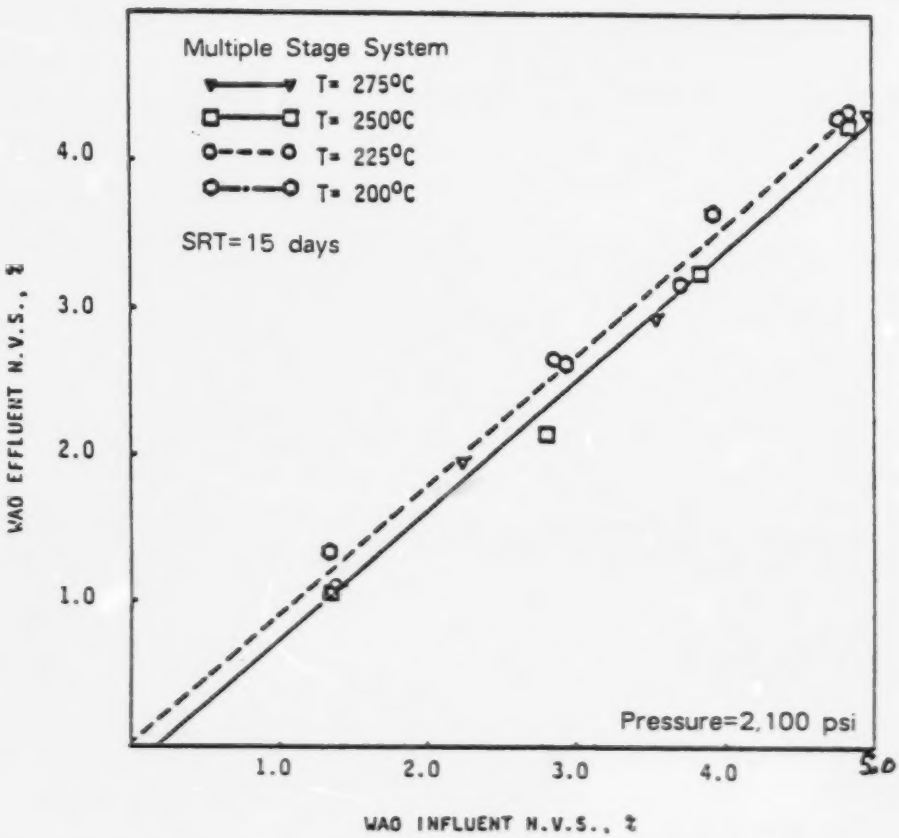


Figure 38: Percent Non-volatile Solids in WAO Influent and Effluent at Various Temperatures

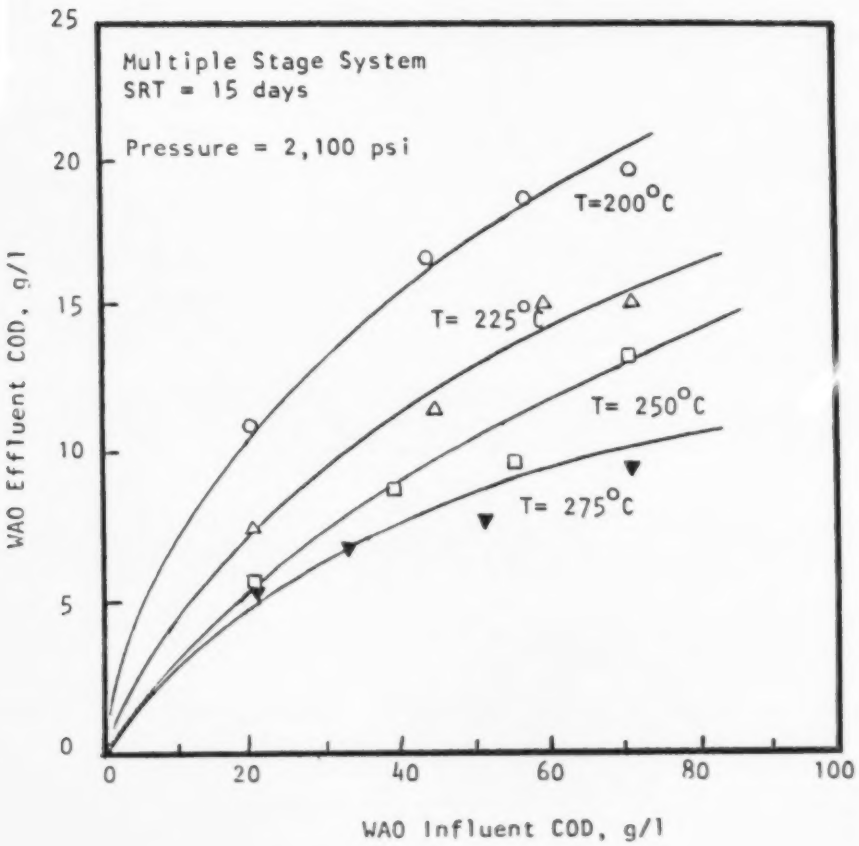


Figure 39: WAO Influent and Effluent COD at Different Temperatures

The WAO of a filter cake with volatile solids concentrations of 0.7 to 9% was investigated. The filter cake was prepared by first adding 600 mg/l of organic polymer (American Cyanamid Company Magnifloc 1563C) to the digested sludge and then dewatering it by vacuum filtration. The experimental results are shown in Figures 40 to 42.

The data on WAO at 275 °C showed that there was no significant difference in the results with sludges taken from the single stage and from the multiple stage system. The non-linear form of the data in Figure 40 is probably due to an oxygen limiting condition. According to Figure 41, the availability of oxygen for further destruction of the WAO influent solids is low soon after the total VS reduction reaches 25,000 mg/l or 2.5%. Figure 42 illustrates that the destruction of the non-volatile portion of the filter cake seemed to be a direct function of the WAO influent non-volatile solids concentration.

The thermal oxidation of sludge solids produced considerable organic volatile acids as shown in Figure 43. At temperatures below 150°C, all of the organic acids increased, with acetic acid being present in the largest quantities, followed by propionic and butyric acids. However, propionic and butyric acids decreased and acetic acid increased rapidly after the temperature exceeded 150°C The acetic acid then decreased when the temperature was in excess of 225°C.

The effect of influent total solids concentration on organic acids generation by WAO is shown in Figure 44. An increase in influent total solids increased the concentration of acetic acid and the volume of CO_2 production. Propionic acid and butyric acid increased as the total solids concentration increased up to 6.4%, but decreased significantly after the total solids concentration exceeded 6.4%. This result again indicated that at the constant temperature and pressure, the oxidation of sludge solids became less efficient due to low oxygen availability. As the sludge concentration increased, this effect became more significant.

The thermo-decomposition of digested sludge to various nitrogen compounds and organic acids was studied and the results are summarized in Tables 25 and 26. The study was performed with the thermophilically digested sludges from the multiple stage system operated at SRT=9 days. The tables generally indicate that as the oxidation temperature was increased from 150 to 275°C, the organic nitrogen was broken down to form major products of ammonia nitrogen, nitrite and nitrate.

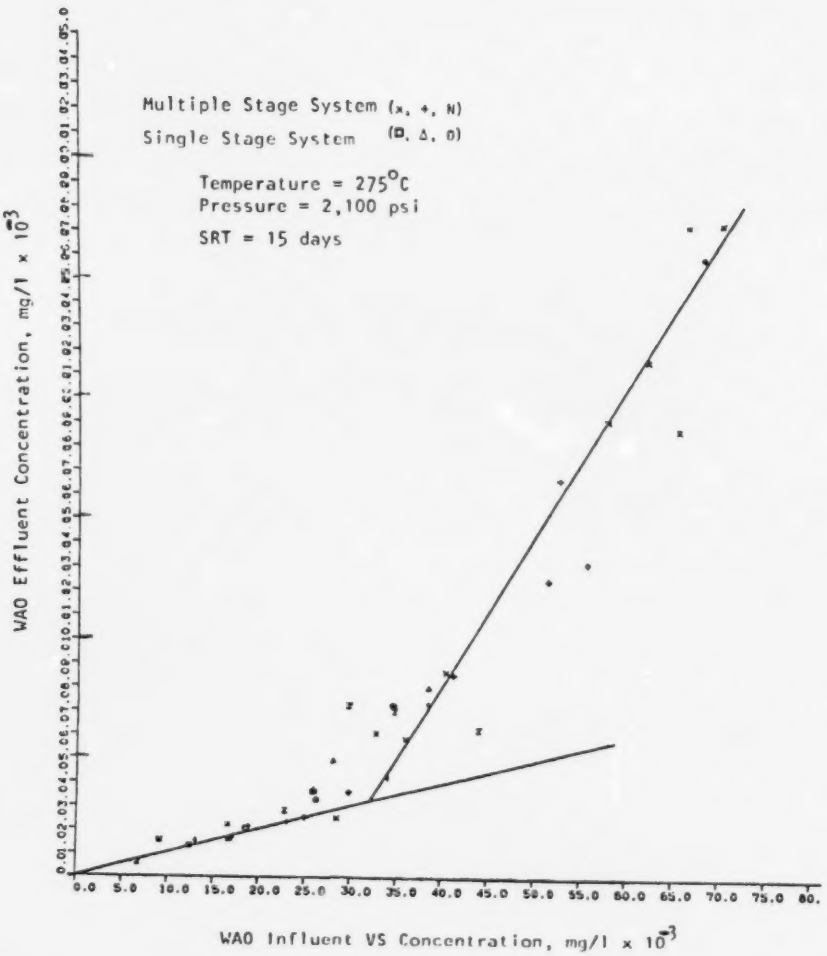

Multiple Stage System (x, +, N)
Single Stage System (□, Δ, o)
Temperature = 275°C
Pressure = 2,100 psi
SRT = 15 days
WAO Effluent Concentration, mg/l x 10^-3
WAO Influent VS Concentration, mg/l x 10^-3
0.0 5.0 10.0 15.0 20.0 25.0 30.0 35.0 40.0 45.0 50.0 55.0 60.0 65.0 70.0 75.0 80.

Figure 40: Efficiency of WAO Treatment on the Destruction of Volatile Solids in Filtration Cake

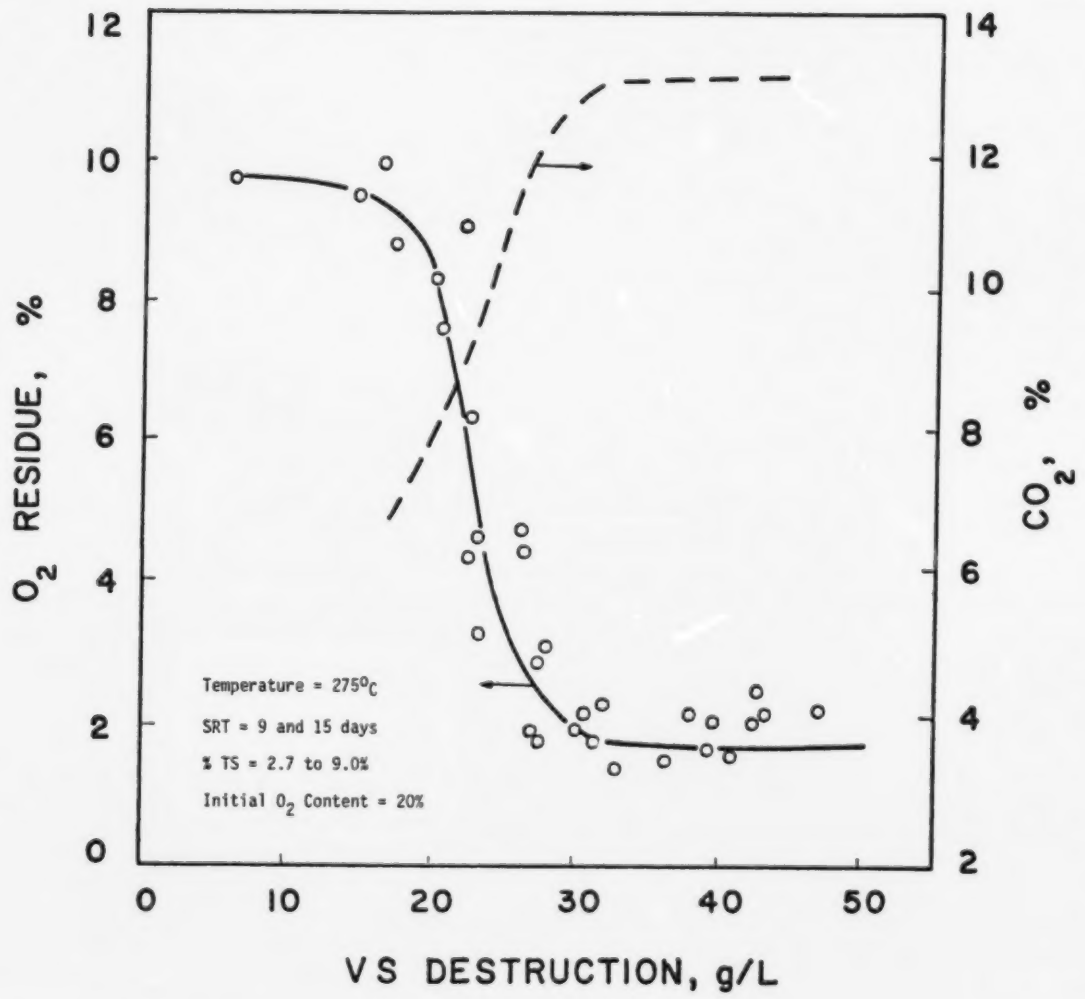


Figure 41: General Reltionship between Oxygen Residue, CO_2 Production and Volatile Solids Relation in WAO Treatment

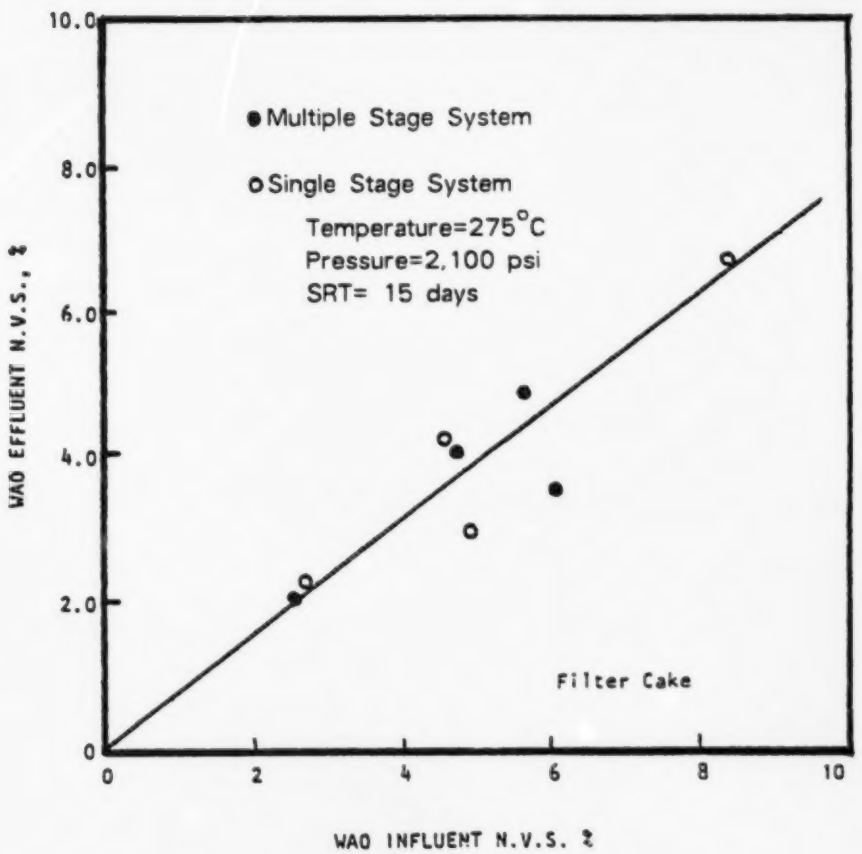


Figure 42: Efficiency of WAO Treatment on the Destruction of Non-volatile Solids in Filtration Cake

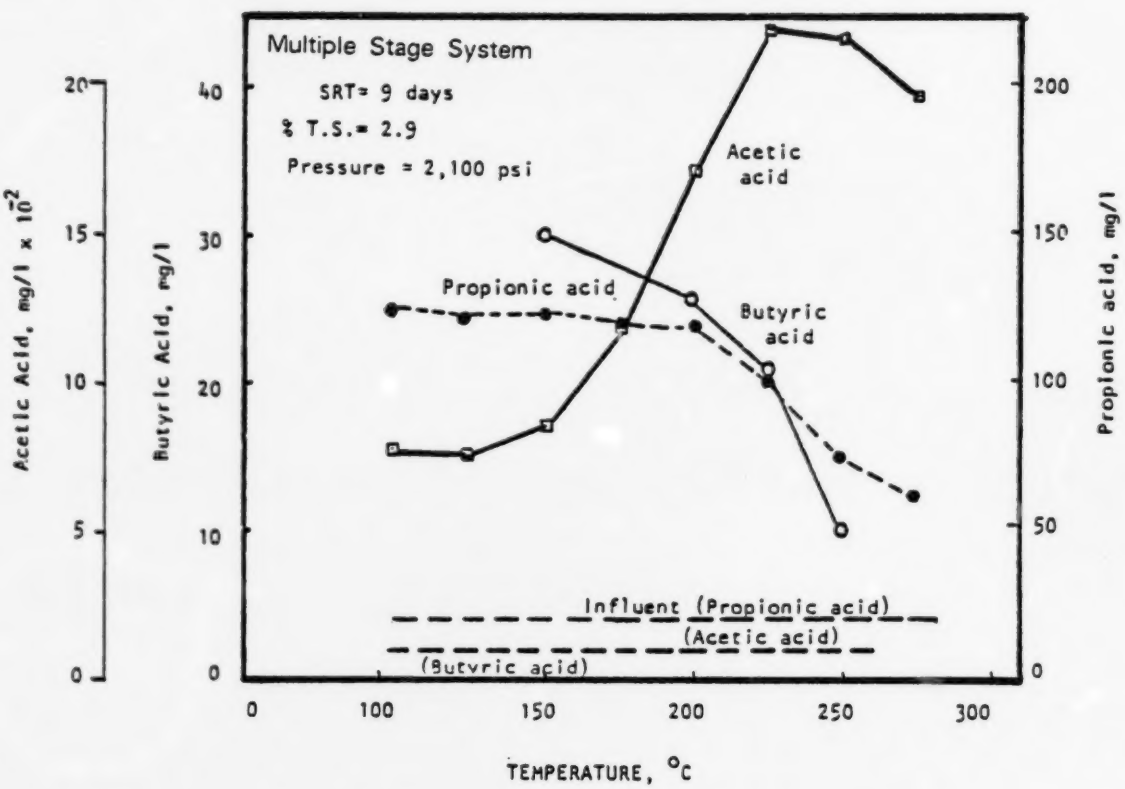


Figure 43: Production of Organic Acids at Different Temperatures

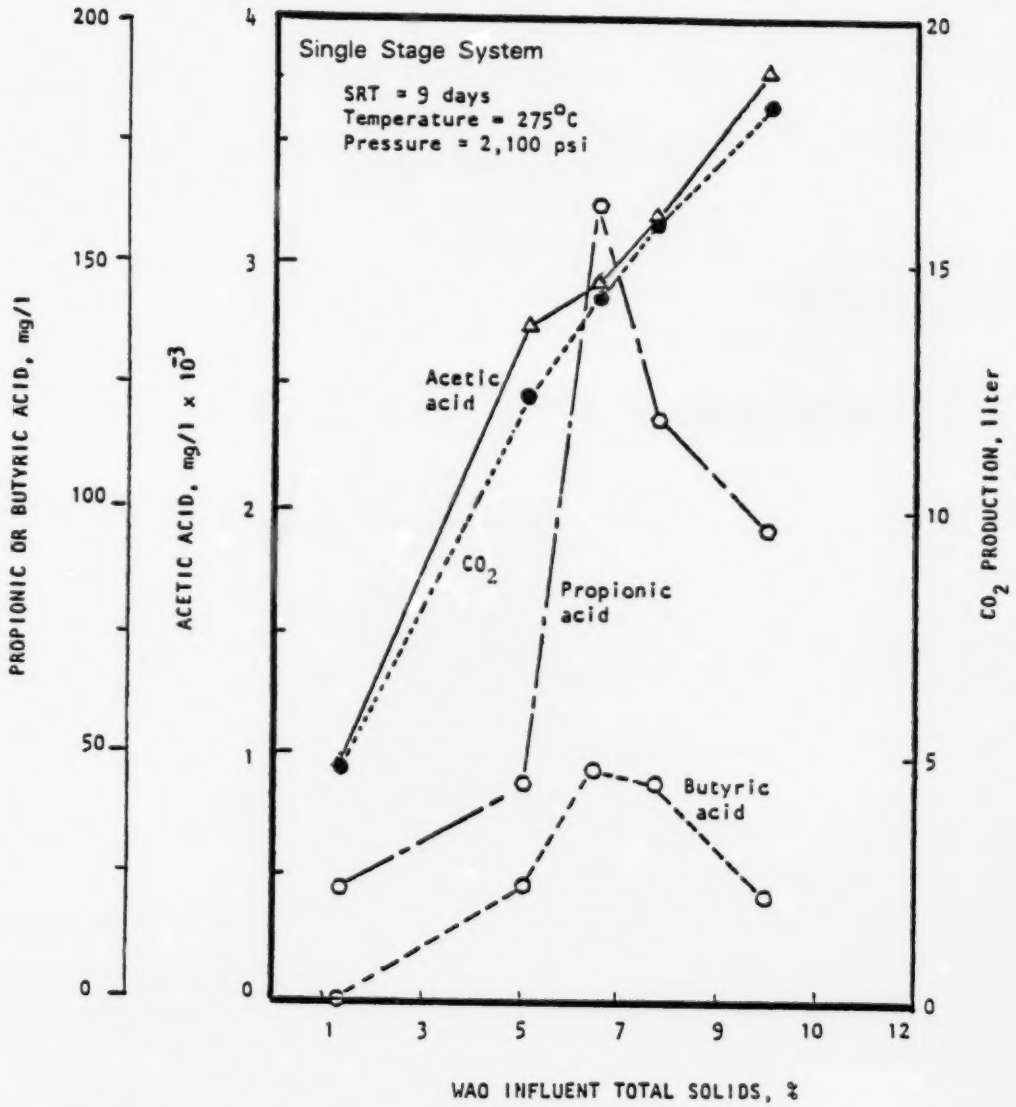


Figure 44: Effect of WAO Influent Total Solids Concentration on Organic Acids and CO_2 Production

Phosphorus concentrations are shown in Figure 45 which indicates that the WAO effluent soluble phosphorus concentration was inversely affected by temperature; that is the higher the temperature the lower the phosphorus concentration. This result showed that phosphorus might combine with metals to form precipitates in WAO treatment at high temperature.

The thermal destruction of digested sludges primarily generated organic acids, nitrogen compounds carbon dioxide, and water, and the products from these reactions affected the pH of WAO effluent supernatant. As shown in Figure 54, the pH increased at temperatures between 200°C and 225°C. Only the sludges with 7% and 9% solids increased between 225°C and 250°C. No significant change in pH was found when the sludge was oxidized at temperatures between 250°C and 275°C, except for the sludge with 9% solids. In most cases, the WAO effluent pH was slightly basic.

The settling characteristics of WAO sludges as expressed by SVI, are also shown in Figure 54. The sludge settleability was influenced by temperature and percent total solids; the higher the temperature or the higher the percent total solids content the better the sludge settleability or the smaller the SVI value.

The stablization of metals by the WAO process was also addressed by this investigation. Measurements of Cd, Cu, Mn, Ni, Pb, and Zn (Tables 27 and 28) in the WAO influent, effluent, and effluent filtrate showed that Cd and Pb were never detected in the filtrate, and Mn, Ni, and Zn were only occasionally detected at low concentrations in the filtrate. Cu was detected in all of the filtrate samples. It is postulated that the metals in the WAO influent sludge were oxidized to form metal oxides, metal hydroxides, etc. and precipitated with the WAO effluent residuals. With respect to the WAO treatment, the metal oxidation and precipitation were not significantly affected by the range of temperatures and solids contents covered by the present study.

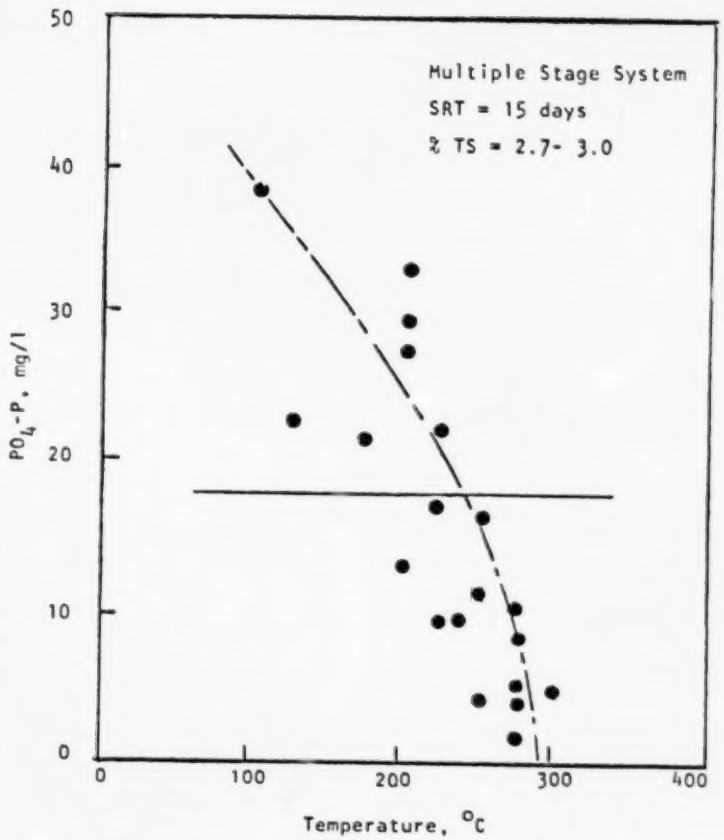


Figure 45: Effect of Temperature on Soluble **Phosphorus** Production

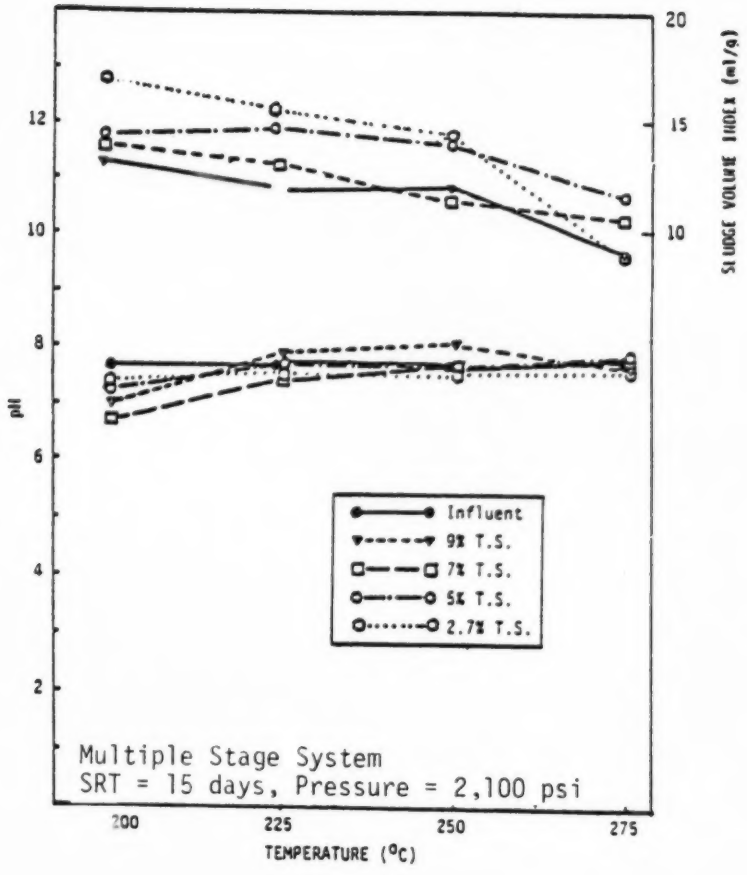


Figure 46: Effects of Temperature and Total Solids Content on pH and SVI

Table 25: Effect of Temperature on Sludge Transformation in WAO

Parameter	150°C				195°C			
	WAO INFLUENT		WAO EFFLUENT		WAO INFLUENT		WAO EFFLUENT	
	Conc. (1)	Conc/Solids (2)	Conc. (1)	Conc./Solids (3)	Conc. (1)	Conc./Solids (2)	Conc. (1)	Conc./Solids (3)
% VS Reduction	44.0				70.61			
Nitrogen Compounds:								
NH_3-N	1,137.55	76.66	855.17	129.36	1,216.09	79.52	1,517.80	140.42
NO_2-N	8.89	0.59	47.14	7.12	15.16	0.99	64.76	5.99
NO_3-N	4.45	0.29	53.81	8.12	11.92	0.78	70.67	6.54
Organic-N + NH_3-N	3,213.29	216.54	1,143.91	172.77	3,497.08	228.70	1,869.20	172.93
Organic Acids								
Acetic acid	68.95	4.64	246.00	37.15	65.00	4.25	1,000.00	92.51
Propionic acid	39.72	2.67	40.00	6.04	37.19	2.43	50.00	4.63
Butyric acid	0	0	26.00	3.92	0	0	23.00	2.13

Units: (1) Concentration in mg/l
(2) Conc./VS oxidized in mg/g
(3) Conc./VS Destroyed in mg/g

Table 26: Effect of Temperature on Sludge Transformation in WAO

Parameter	235 °C				275 °C			
	WAO INFLUENT		WAO EFFLUENT		WAO INFLUENT		WAO EFFLUENT	
	Conc. (1)	Conc/Solids (2)	Conc. (1)	Conc./Solids (3)	Conc. (1)	Conc./Solids (2)	Conc. (1)	Conc./Solids (3)
% VS Reduction	92.15				94.88			
Nitrogen Compounds:								
NH_3-N	716.50	70.41	1,342.60	143.16	547.12	80.43	1,089.02	168.73
NO_2-N	7.39	0.72	44.27	4.72	8.55	1.25	33.20	5.14
NO_3-N	3.01	0.29	48.21	5.14	7.41	1.09	26.40	4.09
Organic-N + NH_3-N	2,515.78	247.22	1,725.99	184.06	2,013.27	295.98	1,876.73	290.78
Organic Acids								
Acetic acid	48.00	4.71	900.00	95.96	35.00	5.14	975.00	151.07
Propionic acid	28.00	2.75	45.00	4.79	15.00	2.21	22.00	3.40
Butyric acid	0	0	7.00	0.76	0	0	0	0

Units: (1) Concentration in mg/l
(2) Conc./VS oxidized in mg/g
(3) Conc./VS Destroyed in mg/g

Table 27. Metals (Cd, Cu, Mn) Concentration in WAO Influent and Effluent

Test No.	Operating Conditions T,°C	P,psi	Total Solids %	Cd Inf	Cd Eff	Cd Fil	Cu Inf	Cu Eff	Cu Fil	Mn Inf	Mn Eff	Mn Fil
1-1	276	2060	2.65	59	89	0.00	1279	921	2.00	10716	894	0.00
1-2	249	1760	2.64	59	113	0.00	1279	913	0.60	10716	1052	0.00
1-3	227	1450	2.59	59	114	0.00	1279	825	2.20	10716	1056	0.06
1-4	205	1295	2.61	59	142	0.00	1279	699	3.36	10716	968	0.06
3-1	276	2160	9.20	66	116	0.00	1401	950	0.54	2280	853	0.06
3-2	250	2160	8.93	66	100	0.00	1401	967	0.90	2280	853	0.06
3-3	227	2030	8.79	66	111	0.00	1401	970	3.20	2280	980	0.00
3-4	200	2050	8.85	66	113	0.00	1401	964	9.64	2280	1105	0.00
4-1	276	2160	4.23	64	88	0.00	1415	1489	3.70	8060	652	0.00
4-2	250	2220	5.18	64	83	0.00	1415	1305	1.35	8060	631	0.34
4-3	225	2050	5.43	64	64	0.00	1415	1106	2.65	8060	548	0.00
4-4	200	2070	5.38	64	69	0.00	1415	968	8.70	8060	455	0.00
5-1	250	2150	7.24	72	121	0.00	1342	968	2.30	2410	1081	0.34
5-2	227	2040	7.57	72	121	0.00	1342	899	3.20	2410	1307	0.00
5-3	200	2070	7.36	72	99	0.00	1342	501	11.00	2410	1323	1.32
5-4	275	2150	6.62	72	91	0.00	1342	991	1.00	2410	950	0.34

Note: Inf = Influent sludge, Eff = Effluent sludge, Fil = Effluent filtrate.

Influent sludge -- SRT = 15 days in the three-stage system.

Units: Sludge, mg/kg; Filtrate, mg/L.

Table 28. Metals (Ni, Pb, Zn) Concentration in WAO Influent and Effluent

Test No.	Operating Conditions		Total Solids	Ni			Pb			Zn		
	T,°C	P,psi	%	Inf	Eff	Fil	Inf	Eff	Fil	Inf	Eff	Fil
1-1	276	2060	2.65	103	286	0.00	184	868	0.00	7466	10660	0.00
1-2	249	1760	2.64	103	401	0.00	184	576	0.00	7466	10560	0.00
1-3	227	1450	2.59	103	329	0.00	184	578	0.00	7466	10120	0.45
1-4	200	1295	2.61	103	316	0.00	184	415	0.00	7466	9016	0.99
3-1	276	2160	9.20	133	386	0.00	124	554	0.00	8405	1969	1.33
3-2	250	2160	8.93	133	466	0.00	124	828	0.00	8405	12320	0.63
3-3	227	2030	8.79	133	279	0.00	124	566	0.00	8405	10380	1.12
3-4	200	2050	8.85	133	0	1.67	124	1150	0.00	8405	11820	8.49
4-1	276	2160	4.23	131	424	0.00	148	760	0.00	8342	6008	0.00
4-2	250	2220	5.18	131	264	1.00	148	632	0.00	8342	6127	0.00
4-3	225	2050	5.43	131	232	1.02	148	629	0.00	8342	5922	0.74
4-4	200	2070	5.38	131	232	1.02	148	627	0.00	8342	5903	2.67
5-1	250	2150	7.24	146	236	0.00	146	1223	0.00	8383	9935	0.00
5-2	227	2040	7.57	146	469	2.03	146	1449	0.00	8383	10930	0.49
5-3	200	2070	7.36	146	160	1.67	146	964	0.00	8383	8262	0.41
5-4	275	2150	6.62	146	443	0.00	146	1231	0.00	8383	9548	0.00

Note: Inf = Influent sludge, Eff = Effluent sludge, Fil = Effluent filtrate.

Influent sludge -- SRT = 15 days in the three-stage system.

Units: Sludge, mg/kg; Filtrate, mg/L.

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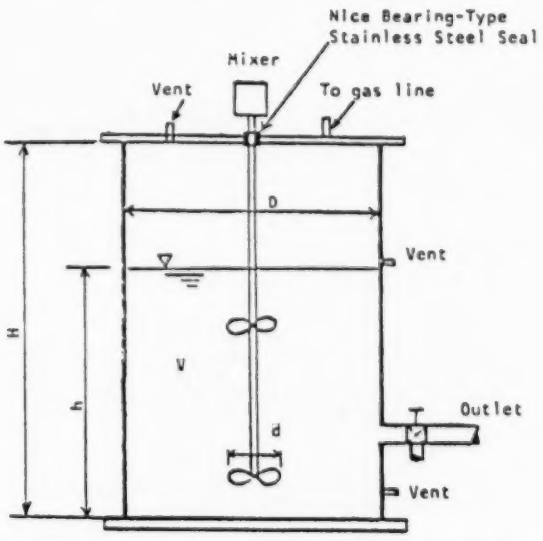
APPENDIX A

DIMENSIONS OF THE ANAEROBIC DIGESTER

Parameter	Test System		Control System	
	Stage 1	Stage 2	Stage 3	One Stage
Total Depth(H)	36"	36"	36"	36"
Effective Depth(h)	27.31	28.56	8.75	25.68
Diameter (D)	8.0"	17.5"	13.5"	17.5"
Total Effective Volume(V)	6gal	30 gal	18 gal	27 gal
Mixer Diameter (d)	5.5"	5.5"	5.5"	5.5"
Rotational Speed rpm	120	200	160	220



APPENDIX B

(A) Calculation of Oxygen Demand

$$O_2 \text{ required} = CODs \times V_s \times (\% \text{ oxidation}/100)$$

where:

CODs = chemical oxygen demand of sample (g/l)
V_s = sample volume (l)
700ml (min. volume required to immerse mixer)

To assure complete oxidation, % oxidation is set at 120 (by Zimpro recommendation). For a sample with COD of 25 g/l and a sample volume of 1 liter:

$$O_2 \text{ required} = 25 \times 1 \times 1.2 = 30 \text{ g}$$

To find the volume of air (V_a) required at STP, use the equation:

$$V_a = O_2 \text{ req.} \times \left(\frac{1}{\text{density of } O_2 \text{ at STP}} \right) \times \left(\frac{\text{volume of air}}{\text{unit vol. of } O_2} \right)$$

Since the density of O_2 is 1.3 g/l at STP, and air is 21% O_2, the above equation can be simplified to:

$$V_a = (O_2 \text{ req.}) \times \left(\frac{1}{1.3 \text{ g/l}} \right) \times \left(\frac{1}{0.21} \right)$$

$$= 3.66 \times (O_2 \text{ req.})$$

For this example:

$$V_a = 3.66 \times 30 = 110.1$$

(B) Calculation of Charging Pressure

$$P_{charge} = \frac{P_{STP} \times V_{STP}}{T_{STP}} \times \frac{T_{charge}}{V_{dome}}$$

where:

P_{STP} = 14.7 psia
T_{STP} = 25°C or 298°K
V_{STP} = V_a (from above)
T_{charge} = charging temperature (room temp.)
V_{dome} = volume of reactor not occupied by sample

In this case, $T_{charge} = T_{STP}$, and $V_{dome} = V_r - V_s$, where V_r is the reactor volume of 3.8 liter. The above equation becomes

$$P_{charge} = \frac{14.7\ (V_a)}{V_r - V_s}$$

and for this example:

$$P_{charge} = \frac{14.7\ (110)}{(3.8 - 1)} = 578 \text{ psia or } 563 \text{ psig}$$

To find the operating pressure, we apply the ideal gas law, but since water vapor pressure becomes significant at high pressure, we must introduce a term to account for this.

The modified ideal gas equation is:

$$\text{Final pressure} = (P_{charge}) \times \frac{T_{op}}{T_{charge}} + V.P.(H_2O)$$

where:

T_{op} = operating temperature
$V.P.(H_2O)$ = $V_a$por pressure of water at the operating temp.

For this example, let us assume an operating temperature of 225°C (498°K):

Final pressure = (578) x (498/298) + 370 psi
= 1,336 psia or 1,321 psig